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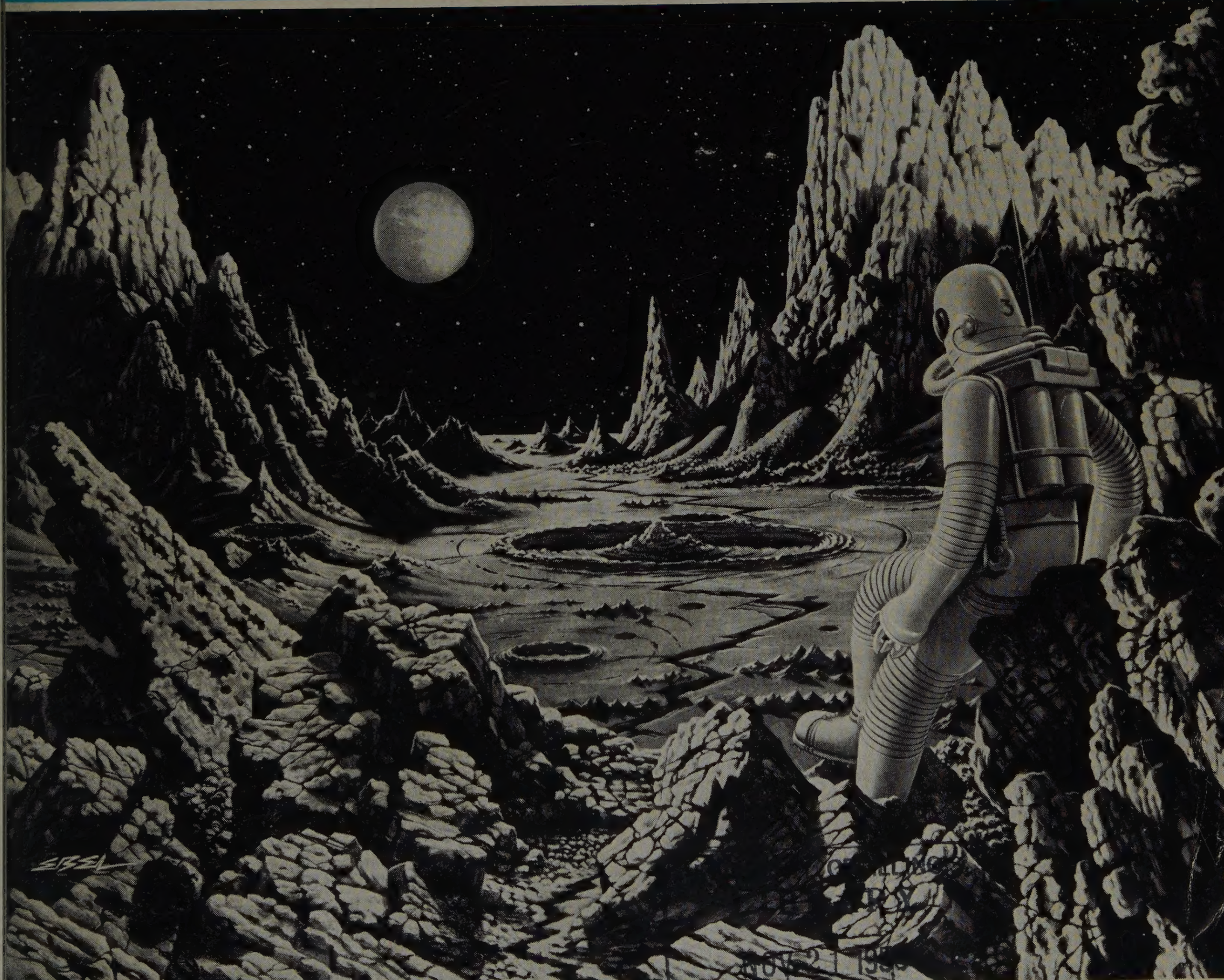

■ INCORPORATING THE ASTRONAUTICAL SCIENCES REVIEW

THE JOURNAL OF THE ASTRONAUTICAL SCIENCES

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Fundamentals of Inertial Guidance and Navigation

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ɔstract

Some of the basic concepts of the science of inertial navi-tion and guidance, including possible applications to space ght and astronautics are discussed. The principle of the huler pendulum and the fundamentals of accelerometers e described. The mathematical solution for a hypothetical celerometer system, consisting of three accelerometers and ree gyros, which performs the same function as a Schuler ndulum, is derived. It is suggested that other possible nfigurations might consist of ordinary pendulums em-oyed as accelerometers using gravity as the restoring rque. Accelerometers are practical for use in gravity-free ace since they do not measure forces due to gravity.

ıtroduction

Aspects of the problem of self-contained navigation y means of dynamic measurements, and their applica-on to aircraft navigation in particular, have been ɔnsidered as far back as the early 1920's, but only nce the last war have the full implications of the roblem been recognized and the development of true ertial-navigation and guidance instruments been alized. The great impetus for the development of ɪis equipment has come primarily from the guidance quirements for missiles and pilotless aircraft, eginning with the German V-2 rocket and continuing ɔ the present day with the Snark, Navaho, Redstone, CBM and IRBM missiles, and others.

At the same time, the application of inertial naviga-on to manned aircraft has not been neglected. Re-ently, information was released to the press about the anscontinental flight, early in 1953, (Ref. 1) of a -29 from Boston to Los Angeles controlled entirely y inertial-navigation equipment developed by the ıstrumentation Laboratory of MIT. This flight had reated quite a sensation when it was announced the ay after it occurred at a classified symposium on ıertial guidance in Los Angeles.

he Schuler Pendulum

In 1923, there appeared in the German physics ɔurnal, Physikalische Zeitschrift, a historic paper by lax Schuler (Ref. 2), an expert on gyroscopic instru-ıents, who worked for Anschutz Kaempfe, a gyro de-velopment and manufacturing concern in Kiel, Ger-many. Schuler is believed to be still actively working for the same company today.

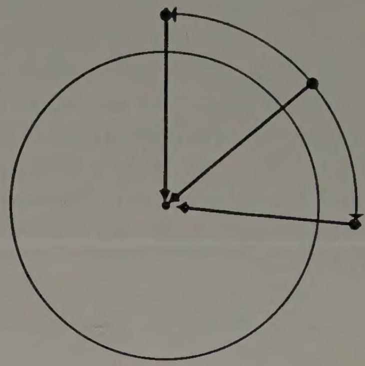

Fig. 1. The Schuler Pendulum

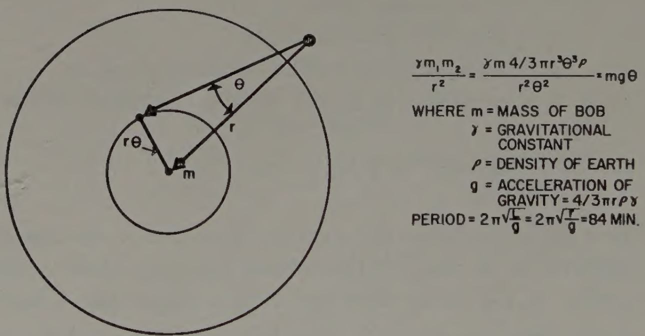

Fig. 2. Displaced Schuler Pendulum

In this paper, entitled "The Disturbance of Pendulum and Gyroscopic Apparatus by the Acceleration of the Vehicle," Schuler gives a solution to the problem of devising an apparatus which will indicate the direction of the true local vertical regardless of the accelerations experienced by the vehicle containing the apparatus.

The direction of the vertical on the surface of the earth is obtained conventionally by the use of a plumb bob; that is, a mass suspended by a thread from a fixed point of support. Such a device is also a pendulum, and if the mass is disturbed a small amount from the vertical and released, it will oscillate with a period determined by the length of the supporting thread and the acceleration of gravity g. Also, if the point of sup-port of the plumb bob is moved from rest, the plumb

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bob will be deflected from the vertical by an amount proportional to the acceleration of the point of support.

Let it now be assumed that the supporting thread is lengthened and that the bob can freely penetrate the earth until the thread is equal to the radius of the earth. Then the bob of the pendulum will be at the center of the earth. If now the point of support is moved around in any way on the surface of the earth (assumed to be exactly spherical), the position of the bob will remain at the center of the earth, and the thread will always lie along the vertical no matter how the point of support is accelerated about on the surface of the earth (see Fig. 1).

Let it be assumed further that the bob is displaced from the center of the earth so that the supporting thread makes a small angle θ with respect to its former equilibrium position (Fig. 2). If the earth is assumed to be homogeneous, the gravitational force on the bob is just that due to the mass lying within the sphere of radius $r\theta$ about the center and is directed toward the center. The magnitude of the force is by the Law of Gravitation:

$$\frac{\gamma m_1 m_2}{r^2} = \frac{\gamma m \, \frac{4}{3}\pi r^3 \theta^3 \rho}{r^2\theta^2} = mr\rho \, \frac{4}{3} \, \pi r\theta = mg\theta$$

where r = distance to center of earth
m = mass of the bob
γ = gravitational constant
ρ = density of the earth (assumed constant)
g = acceleration of gravity at the surface of the earth $= \gamma \, \frac{4}{3} \, \pi r\rho$

This restoring force has exactly the form of the force exerted on a simple pendulum hanging above the surface of the earth. The period of a simple pendulum is just $2\pi\sqrt{L/g}$ where L is the length of the pendulum. Here, for our earth's radius pendulum, $L = r$ and hence the period of oscillation is $2\pi\sqrt{r/g}$ or 84 minutes. Hence the name "84-minute pendulum" or "Schuler pendulum" for such a device. If the pendulum is displaced from the vertical and released, it will oscillate with an 84-minute period.

Such a simple pendulum is obviously impossible to realize physically. However, we can, in principle, replace any simple pendulum by a compound or physical pendulum having the same period and the same properties as the simple pendulum. By definition, a compound pendulum is merely a rigid body pivoted at a point displaced from its center of mass. Unfortunately, even a compound pendulum with an 84-minute period cannot be built, since even for a very large and heavy body, the displacement of the pivot from the center of mass must be less than a thousandth of a millimeter in order to have a period approaching 84 minutes. In addition, a frictionless support for the physical pendulum would be required for proper operation.

Schuler attempted to simulate the 84-minute pendu lum with a pendulous gyroscope, but he indicated th he never succeeded in getting a period longer than minutes. His intention was, of course, to construct artificial horizon which, together with star sigh would give an accurate fix in an airplane regardless maneuvers and accelerations of the vehicle. Clearly, Schuler pendulum together with a clock, an automa star tracker, a compass (or another star tracker), a nautical almanac could be used to measure positi on the earth uniquely and thus could provide automa guidance or navigation. Alternatively, since a free gy tends to maintain its orientation in inertial space (a if initially pointed at a particular star, will mainta that orientation), the star tracker can be replaced by gyroscope and we then have a true self-contain inertial-guidance system consisting of an indication the true local vertical and an inertial orientation refe ence. The big problem then is to build drift-free gyr for the inertial direction indication.

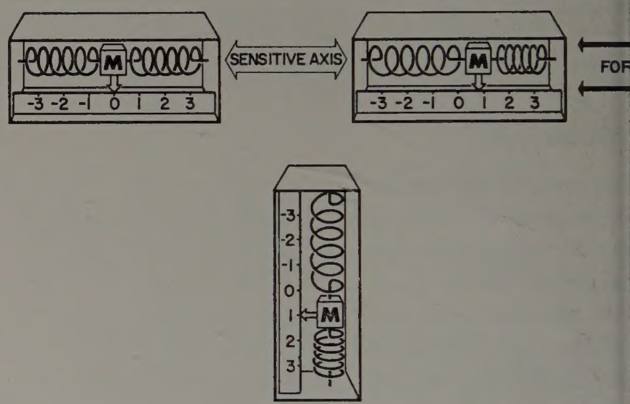

Fig. 3. Operation of Simple Accelerometer

Accelerometers and What They Measure

Let us now consider some of the building bloc that make up an inertial navigation system. T primary measuring instrument in an inertial system the accelerometer, which means literally "measurer acceleration". As the archetype of an acceleromet we will use the simple device of a proof mass on a spri where the measure of acceleration is the deflection the mass from the position of equilibrium (see Fig. If the accelerometer is subjected to a force acting towa the left, then the accelerometer will be accelerated the left and the proof mass will be deflected to the rig with respect to the case by an amount proportional the acceleration.

Let us now place our accelerometer upright on table top. Because of the force of gravity acting on t proof mass, it will be deflected downward, and t accelerometer will indicate that it is being accelerat upward. However, if we examine the forces acting the accelerometer, we find that there are really t equal and opposite forces acting: one the force of grav acting downward, and the other the reaction force

ne table on the accelerometer. Thus we can say that ne accelerometer is subjected to a specific force (force er unit mass) or acceleration due to gravity acting ownward and an acceleration due to the reaction f the table acting upward. The resultant total acceleration is the vector sum of the two components nd since they are equal and opposite, the accelerometer emains at rest in equilibrium despite the reading of ne accelerometer of one g acceleration upward.

Let us now remove the table and allow the accelerometer to fall freely toward the earth. The accelerometer will now read zero since, like the man nside the freely falling elevator of Eddington's famous xample, the gravitational force acts alike on the accelerometer case and the proof mass appears to experience no gravitational force acting on it. However, we now that the accelerometer is actually being accelerated downward with an acceleration g.

From these two examples, we arrive at the important onclusion that *an accelerometer does not indicate the cceleration of gravity, but reads only the nongravitational ccelerations to which it is subjected* (Ref. 3). It is presely for this reason that navigation by means of accelerometers is so complicated. If an accelerometer neasured the resultant of all accelerations to which it s subjected, both gravitational and nongravitational ccelerations, then the resultant position of the system s a function of time could be obtained immediately y simply doubly integrating the accelerometer readng. Instead, it is necessary to compute the acceleration f gravity continuously and add it to the reading of ne accelerometer in order to obtain the true resultant cceleration which can then be doubly integrated to btain position.

Simple Accelerometer System

Let us examine now what is required to make a simple osition-measuring system using accelerometers. The ehicle to be measured in its motion must obey Newton's law of motion, according to which the mass imes the total acceleration must equal the sum of all orces acting on the system. The forces can be separated nto two kinds: the gravitational force and nongravitaional forces (which include reaction forces to gravity). t can then be stated that the total acceleration, the ouble integration of which is position, is equal to the ravitational acceleration, which must be computed, lus the nongravitational acceleration (due to aerodyamic lift and drag, propulsive forces, and wind forces) which is measured by the accelerometers.

In order to measure the nongravitational acceleraion, one can employ three linear accelerometers riented mutually perpendicularly. This arrangement will just suffice to determine completely the nongravitaional accelerations. The three accelerometers must be tabilized, and we choose a nonrotating inertial frame f reference which can be established by means of yroscopes which maintain a fixed inertial attitude when

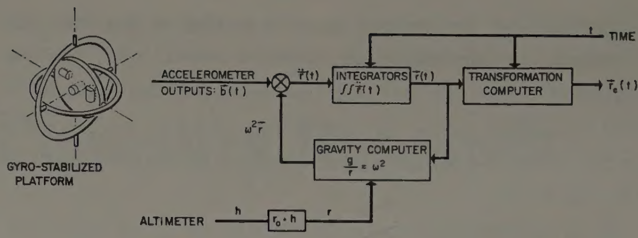

FIG. 4. Block Diagram of Inertial Navigator

perfectly balanced to eliminate disturbing torques (see Fig. 4). To the accelerometer outputs, we must add the computed gravity acceleration components, thus giving the true acceleration of the system. This is then doubly integrated to give position, which output can then be used for the gravity computation. The output is the position in the inertial frame of reference, and since we are interested in position with respect to a rotating earth, this output is fed into a transformation computer which transforms the output to position with respect to the earth by taking into account the rotation of the earth.

The equation of motion for the system can be written:

Mass × Acceleration = Gravitational Force + Nongravitational Force

or

$$m\frac{d^2\vec{r}}{dt^2} = m\vec{g} + m\vec{b}(t)$$

where $\vec{r}$ = position vector
$\vec{g}$ = gravitational acceleration
$\vec{b}(t)$ = nongravitational specific force or acceleration measured by the accelerometers

or

$$\frac{d^2\vec{r}}{dt^2} = \vec{g} + \vec{b}(t)$$

The double integration of $\frac{d^2\vec{r}}{dt^2}$ is the position $\vec{r}(t)$ which is the quantity desired.

If position is measured relative to the center of the earth, then the gravitational acceleration can be written:

$$\vec{g} = -\frac{g}{r}\vec{r}$$

where $\vec{r}$ is the scalar distance from the center of the earth to the system and the minus sign indicates that the direction of $\vec{g}$ is radially inward, opposite in direction to the position vector $\vec{r}$.

If the vehicle containing the accelerometer system is constrained to travel at constant altitude by means of an altimeter, then r is constant, and if we designate g/r by ω^2, then the equation of motion can be written:

$$\frac{d^2\vec{r}}{dt^2} + \omega^2\vec{r} = \vec{b}(t)$$

This can be recognized as the equation for an undamped simple-harmonic motion with the driving function $\vec{b}(t)$. The natural frequency of the motion is $\omega/2\pi$ and the period of oscillation is $2\pi/\omega = 2\pi\sqrt{r/g}$ or 84 minutes, since r is the radius of the earth plus the altitude.

It is interesting to note that if $\vec{b}(t) = 0$, we have the case of a satellite traveling in a circular orbit in vacuum about the earth with an orbital period of just 84 minutes.

The equation of motion above shows that the accelerometer system is an analog of the Schuler pendulum, for if it is disturbed (e.g., by having the wrong initial conditions put into the solution), then it can be shown that an error oscillation of the position output of an 84 minute period will result just as in the case where the Schuler pendulum bob is displaced slightly from the vertical.

Other configurations and mechanizations than the one described above are possible. Thus, for example, ordinary pendulums, (not Schuler pendulums) can be used as accelerometers (Ref. 4). In this case, gravity is used as the restoring torque on the proof mass (see Fig. 5). A plumb-bob pendulum, or bubble level, will indicate the direction of the true vertical if held at rest. If the pendulum is suspended in a vehicle which is being accelerated in the horizontal direction with acceleration b, then the deflection of the pendulum from the true vertical is $\tan^{-1}(b/g)$ or, for acceleration b much smaller than g, approximately b/g. If now we measure the angle of the pendulum with respect to the direction of reference vertical at some initial point, then this angle (Φ) is equal to the deflection of the pendulum with respect to the true local vertical (b/g) plus the angle at the center of the earth between the reference vertical and the local vertical (Θ). The reference vertical can be maintained in the vehicle by means of accurate gyros corrected by the earth's rotation.

The tangential acceleration b is given by:

$$b = r\frac{d^2\Theta}{dt^2}$$

Also from Fig. 5:

$$\phi = \frac{b}{g} + \Theta$$

or

$$b = g(\phi - \Theta)$$

Hence, we have the equation of motion:

$$r\frac{d^2\Theta}{dt^2} = g(\phi - \Theta)$$

or

$$\frac{d^2\theta}{dt^2} + \omega^2\theta = \omega^2\Phi$$

where $\omega^2 = g/r$

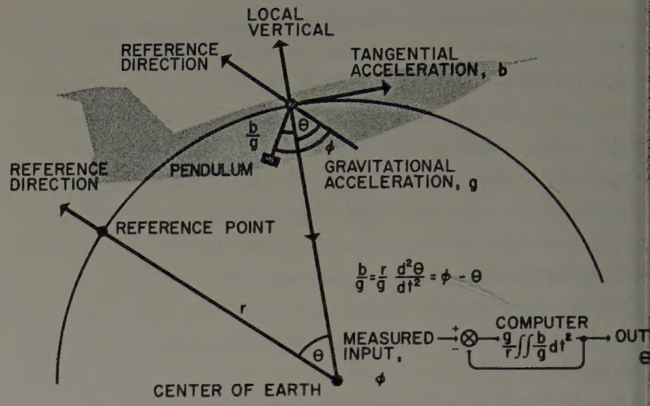

Fig. 5. Operation of Pendulum Accelerometer

The angle θ is a measure of the distance the vehic has traveled from the reference point and hence is th desired quantity. Φ is the measured quantity, the d flection of the pendulum from the reference directio Hence, we must solve the above differential equatio for θ.

This equation is precisely of the same form as th equation of motion for the simple accelerometer syste derived previously and has the same natural frequenc of oscillation of 84 minutes as before. Thus a disturban (e.g., an error in measuring Φ) will cause an undampe error oscillation in position output with a period 84 minutes.

The above equation can be written in another wa which gives a key to the mechanization of the comput tion of position:

$$\theta = \omega^2 \iint (\Phi - \theta)\, dt^2$$

Thus, as shown in Fig. 5, we subtract the output of the computer from the measured quantity Φ an feed this into the input of the computer which multipli by $g/r = \omega^2$ and integrates twice. Then the system w satisfy the above equation and the output will then b the quantity θ, which is the measure of the true positio of the vehicle with respect to the reference point.

Astronautical Applications

It is fairly obvious that inertial systems and, in pa ticular, accelerometer systems are ideal for the measur ment of motion in interstellar space where the proble of gravity computation does not exist, and whe accelerometers measure directly the motion due engine thrust, if any. The obvious inertial referen directions to use are those given by observation of th distant stars and, clearly, automatic star tracke could be used to advantage.

For navigation in the vicinity of gravitationally a tracting bodies, it is necessary to compute the gravit tional forces on the vehicle. These computations can b accomplished with the aid of a measurement of directio and distance from an attracting body, assuming th the mass of the body is known. Such computations ca

(Continued on page 1

Plastic Balloons for Planetary Research

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ıtroduction

The marriage of telescopes and modern plastic ılloons gives promise of making one of the more gnificant contributions to optical astronomy since the ıys of Galileo. The age old problem, a formidable one ɔ those employing optical systems for studying the niverse, is the atmosphere barrier lying between the elescopes and the stars. Thus, because of the earth's tmosphere, clear seeing is not attainable and resoluon suffers.

One approach to combat the problem is to build ırger telescopes. The 200-inch mirror at Palomar, owever, is probably the practical limit to this aproach. And still there are a multitude of unknowns.

A second approach is to climb above the atmosphere ɔ a point where the heavens lie fully exposed to the robes from below. The visionaries dream of satellites nd space ships for this application. Some day their reams will materialize. But why wait? The plastic alloon offers an interim vehicle capability which is vailable *now* for use with stratospheric observatories. dmittedly there will still remain a small residual ortion of the earth's atmosphere (perhaps 2%, alough this is a variable) between the observatory and ıe planets—or other bodies to be investigated. Neverıeless the plastic balloon vehicle is a practical and elatively inexpensive means for the second approach ɔ achieve a significant improvement in seeing. It is the ɔgical step toward space astronomy.

Balloon astronomy and astrophysics can be aimed in ıany directions. Studies of the planetary atmospheres, f course, represent only a portion of the intriguing and hallenging opportunities. The entire universe awaits ɔr further exploration.

. Background

This paper is not intended as a complete documentary f previous balloon astrophysical studies, but some of ıe past experiences and earlier suggestions will be ıentioned to show that the subject is not really new. 'he plastic balloon, however, has made it practical on a ontinuing basis.

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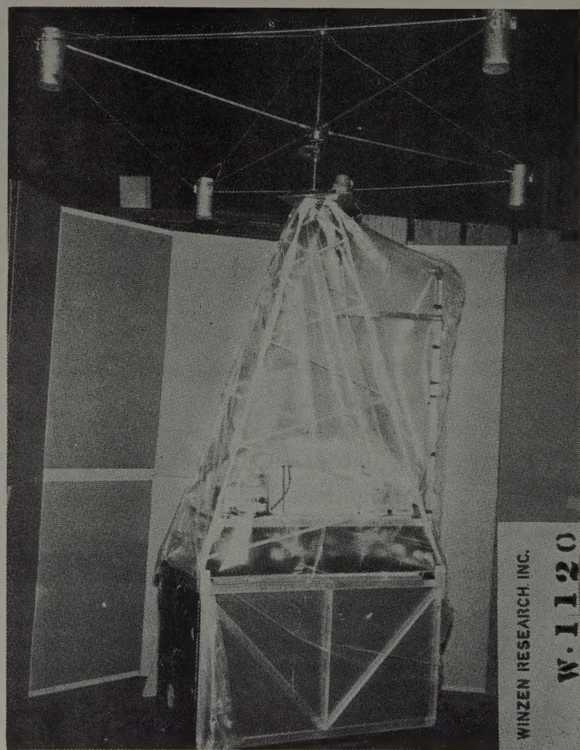

Fig. 1

One of the earliest uses of a balloon for astrophysical observations was made in 1863 by Glaisher in England. One of his famous series of ten scientific balloon flights utilized a form of solar spectroscopy.[1]

It is noted that none of the 10 historic manned stratospheric balloon flights of the 1931–1935 period were equipped with optical systems to exploit the altitudes reached for observations of the planets. Attention, however, was devoted to the sun. Since planning records for all these flights are not available for perusal, it is possible that some considered and then discarded the use of telescopic systems while aloft.

The Soviets, after the first successful flight of the USSR into the stratosphere on September 30, 1933, became keenly aware of the tremendous importance of the manned 'stratostat' for scientific research. The All Union Conference was held early in 1934 to consider the scientific opportunities afforded by stratospheric

balloons. The subsequently issued report[2]—which documents some rather advanced thinking—clearly indicates that balloon astronomy was not seriously considered.

Auguste Piccard, the dreamer, the inventor, the true pioneer, however, in a recount of his stratospheric adventures and a summary of the others during the 1931–1935 period, contemplates the possible future of manned balloons and suggests that planetary observations, with telescope and spectrograph combinations, will be fruitful.[3]

Some work in Europe combining the balloon and telescope has been accomplished by Auduoin Dollfus, a French astronomer-balloonist, son of veteran aeronaut, Charles Dollfus. In 1954 the Dollfus father-son team made an ascent to approximately 20,000 feet in an attempt to make measurements of the water vapor in the atmosphere of Mars. The conclusions[4] were that a much higher altitude would be required to minimize the screening effect of the water vapor in the earth's atmosphere. Dollfus, therefore, is now working on a stratospheric system for extending his Martian studies. For a balloon vehicle he is currently planning to use the cluster technique,[5] first proposed by Jean Piccard and successfully demonstrated by him in 1937.[6]

In a recent visit to the United States Dollfus also discussed experiments conducted by him in collaboration with the British astronomers Dewhirst and Blackwell. During ascents in 1956 and 1957 an 11-inch telescope was used to photograph the sun for studies of the granular solar surface.

In this country the relatively recent developments in plastic balloons—an entire new balloon technology—has resulted in greatly improved balloon capabilities for both manned and unmanned systems. It is a logical and natural consequence, therefore, that careful consideration has been given to their use for extraterrestrial observation.

3. Discussion of Plastic Balloons for Extraterrestrial Research

Professor Jean Piccard flew the first plastic (cellophane) balloons in 1935 in Swarthmore, Pennsylvania, and subsequently expanded his plastic balloon investigations with Dr. Akerman at the University of Minnesota.[7] The plastic balloons referred to here are quite similar, although much larger, and direct descendants of Piccard's original ones. Today's are made (mostly) of polyethylene extruded film joined together with heat sealed gores to achieve the particular size and shape desired.

The entire concept of very high altitude balloon research has changed in the past decade. As a result of the technical achievements in plastic balloon technology and their widespread use in this country under government sponsored research programs the possibilities of balloon astronomy began to be considered seriously a few years ago. The Office of Naval Research, pioneer agency in supporting the plastic balloon as a tool f research under its Skyhook program, has served as catalyst to assist scientists conduct varied experimen from the plastic balloon vehicle.

Vaeth,[8] who reports on the possibilities of a mann Skyhook balloon system for exploratory measuremen of the Martian atmosphere, has helped considerably keep this attractive techinque under consideration for number of years. He and the small group of others w initially recognized the value of this technique must properly credited for their valuable assistance.

The plastic balloon as a system, however, c logically be divided into two basic types. They a manned and unmanned. Skyhook, currently support jointly by the Office of Naval Research and the Atom Energy Commission for studies of cosmic radiation, a prime example of the unmanned plastic balloon. special name, Stratoscope, has been applied to the for of Skyhook which uses an automatic telescope f solar research. Strato-Lab is the designation assign by the Office of Naval Research to its manned syste which employs Skyhook type plastic balloons—an people—for research.

Significant progress has been made with the plast balloon in the past few years, particularly in its cap bility for carrying heavy loads—on the order of a ton and reaching high altitudes. Light payloads of instr ments have been carried as high as 145,000 feet.

One of the first known attempts to carry out a astrophysical measurement from a plastic balloo occurred on June 30, 1954, under the Skyhook program During the solar eclipse of that date two Skyhoo balloons were launched by Winzen Research wit camera gondolas employing simple orienting systems The objective was to photograph the eclipse from hig altitude. Varied photographic equipment was carrie and aimed at the sun to obtain full coverage for th total period of totality.

The Skyhook eclipse attempt was not fully satisfa tory. One of the two flights was at quite low altitud when the eclipse occurred; the other was rising (ther fore rotating too much for the orienter to control) an had not quite reached 80,000 feet when the eclips occurred. It did photograph the entire eclipse, howeve from high in the stratosphere. Figure 1 shows th simple orienter and camera system flown.

Although the eclipse system was relatively crude an results were not spectacular this effort helped provide certain amount of valuable background experienc leading to more refined measurements.

a. Strato-Lab

A few weeks after the solar eclipse flights of 1954 was decided within the Office of Naval Research initiate development of a manned plastic balloon r search system capable of reaching great heights in th stratosphere. The system was named Strato-Lab wit its basic objective to supplement Skyhook for th

FIG. 2

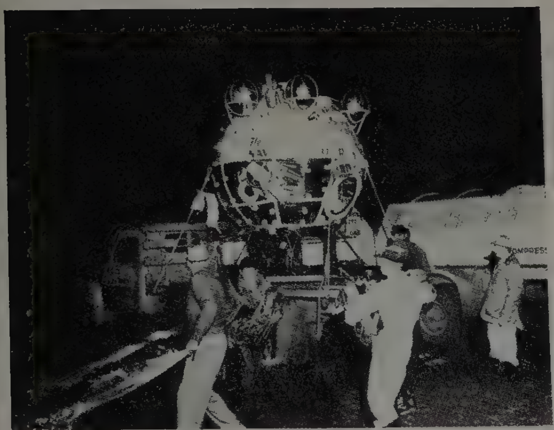

FIG. 3

ertain types of researches which required people board. One of the initial research objectives envioned use of the manned balloon system to look out eyond our atmosphere at the celestial bodies.

As a system the manned plastic balloon has been emonstrated as feasible. Strato-Lab flights with two nan crews have been made for many measurements at variety of altitudes up to almost 86,000 feet.[10] 'lights for major astronomical measurements have not et, however, been made. It appears there are two orms of Strato-Lab which can make significant contriutions in astrophysics and astronomy. One uses a imple open basket gondola with appropriate oxygen for he personnel and is capable of penetrating the turbuent tropopause into the lower stratosphere. The second orm of Strato-Lab provides a sealed cabin with a ompletely artificial atmosphere for the occupants.

A typical Strato-Lab open basket gondola is shown Figure 2. With it there have been three flights made vith two man crews to altitudes of about 40,000 feet. t that point less than 20% of the earth's atmosphere es above the observers. No attempts have been made s yet to use this technique for astronomical observaions but various measurements have been proposed and re under consideration.

It is likely in the near future that star scintillation neasurements will be made in this manner with equipment developed for this purpose at the Naval Observatory under the direction of Dr. John Hall and Mr. A. H. Mikesell. The experimental procedure contemplates night observations at various altitudes on ascent and/or descent to obtain quantitative indications of the variation in stellar scintillations with altitude. These should be important measurements in an area of astronomy where little data are available. These preliminary observations would undoubtedly serve as the basis for subsequent measurements made to much higher altitudes.

Open basket Strato-Lab measurements have also been proposed by Dr. Walter O. Roberts and Dr. Gordon Newkirk of the High Altitude Observatory of the University of Colorado at Boulder. Newkirk has previously used a special photographic sky photometer for studies of the solar aureole out to 3° from the solar limb.[11] The special instrument includes a portable coronagraph to occult the solar disk and allow investigation in the immediate vicinity of the sun. He has proposed using it on open basket Strato-Lab flights so that measurements can be made versus altitude from sea level to about 40,000 feet. It is anticipated that some exploratory measurements will be made in collaboration with Newkirk in the near future.

The second form of Strato-Lab which is suitable for astronomical exploration employs a sealed cabin. Figure 3 illustrates the cabin now available for a two man crew to reach appreciable heights in the stratosphere. On November 8, 1956, it was flown to 76,000 feet[12] and on October 18, 1957, to an altitude of 85,700 feet. Figure 4 is a launch photograph of the more recent flight.

FIG. 4

Professor John Strong of Johns Hopkins University plans to employ the sealed cabin for planetary research.[13] Figure 5 indicates about how his Schmidt telescope system will appear when mounted on the gondola. The system, now under development, uses the Schmidt with a 16-inch primary mirror, a special spectrograph, an automatic star tracker and manual rough control for orientation from within the gondola. The observer will also "trim" the image as needed.

Immediate plans for the Strong system are to obtain spectra of the Martian atmosphere. Two flights are planned for November of this year when Mars again will be in a favorable position. Objective of the first flight will be to determine the water vapor content in the atmosphere of the planet; the second experiment will be aimed at investigating the oxygen content. It is planned on either or (preferably) both flights to examine the solar spectrum during daylight portions of the flights.

Planning beyond the current Mars explorations is, of course, much more general for the Strong version of Strato-Lab. In the long range program, however, are considerations of a concentrated effort to make observations of all the planets in the solar system. Other investigators may also want to consider other problems from the high altitude Strato-Lab observatory.

The flights planned for this November will help determine the feasibility and the future of this form of the plastic balloon vehicle for precise astrophysical data. Preliminary stability measurements made on the flight of October 18, 1957, indicate that the Strong system is compatible with the motion observed in a manned balloon gondola.

b. Stratoscope

This particular designation has been given to the form of Skyhook unmanned system developed by Dr. Martin Schwarzschild and colleagues at Princeton University. At a meeting of the American Astronomical Society in Ann Arbor, Michigan, on June 23, 1954, he proposed that studies of the solar surface be made from high altitude plastic balloons to investigate the granular structure.

It was inevitable that he subsequently met with representatives of the Office of Naval Research who assisted, and eventually supported, his program. Initial measurements were made during 1957 with gratifying results which represent the best quantitative solar surface measurements made to date and the first meaningful results obtained by a completely automatic system for balloon astronomy.[14]

The Stratoscope system includes a 12-inch telescope developed by the Perkin-Elmer Corporation. Figure 6 shows the special tube constructed for the telescope. A precise, light sensitive system was developed by the Research Service Laboratories of the University of Colorado to orient the telescope in a proper manner while airborne. These were wedded into a system for balloon use by engineers of the Balloon Department, Mechanical Division, of General Mills, Inc., Minneapolis. In Figure 7 the complete system is shown mounted on a launching truck. In Figure 8 the Skyhook balloon has been inflated and the system is shown immediately after launch in Figure 9.

STRATO-LAB GONDOLA
WITH "STRONG" TELESCOPE

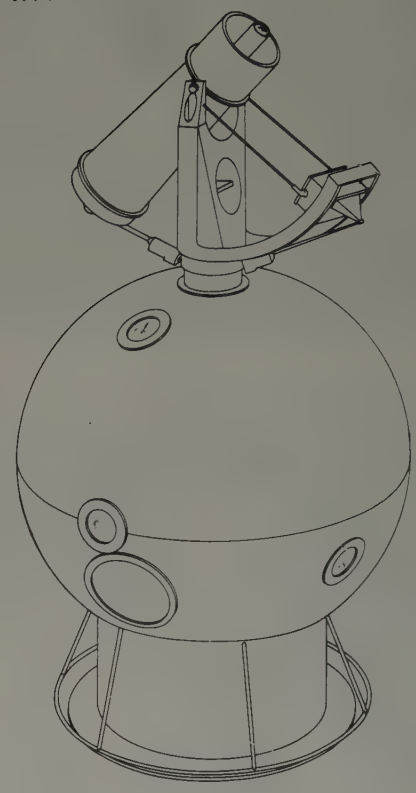

Fig. 5

Two flights were made during this past year. The first, on September 25, 1957, by sheer coincidence, occurred on the 10th anniversary of the first successful flight of a Skyhook balloon. The second flight was made on October 17, 1957.

Experimental results from these two pioneering flights were quite encouraging and it appears that the future will see a vigorous pursuit of research employing the Stratoscope technique. The 12-inch system will be modified to include television scanning and will be supplemented in the future with one having a 36-inch telescope. Long range planning reveals a large number of experiments which can be conducted with these two systems.

4. Future Prospects

When one considers applications of astronomical instrumentation to the Skyhook type of unmanned plastic balloon system (Stratoscope) and to the manned Strato-Lab system it can be concluded that virtually all the major problems in astronomy can eventually be investigated again without the usual atmospheric

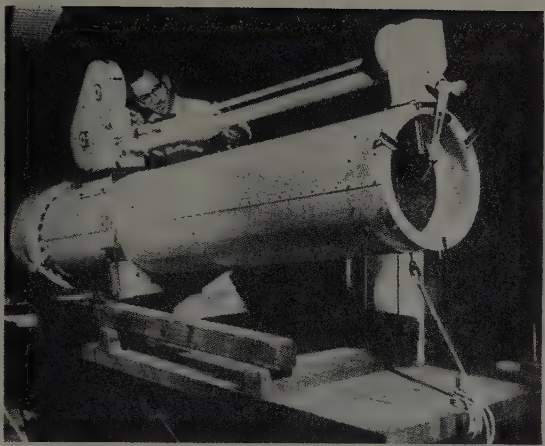

Fig. 6

Fig. 7

disturbance which limits the resolution. Plastic balloon astronomy is not only a stepping stone to satellite and/or true space observatories; it is destined to make its own very positive and important contributions over the next decade or so to a more complete understanding of the universe.

In considering the manned and unmanned techniques together a number of specific—and some general—investigations are now being considered as part of the long range program. These, which are extensions of the measurements discussed above, indicate that our solar system, in particular, is destined to be scrutinized as never before in the near future. Planetary researches within our solar system will receive the primary attention. As a result of informal discussions with Dr. Strong, Dr. Schwarzschild, and others, the following studies appear to be among the ones to be made in the near future with Strato-Lab and Stratoscope: (a) observations of the center of the Andromeda galaxy; (b) investigate the gaseous nebula of Orion; (c) photograph the aurorae on Venus; (d) measure some of the planet diameters; (e) photograph Mercury; (f) photograph the infrared spectra of all the planets; and (g) stellar spectroscopy.

Perhaps radio astronomy equipment can also be applied to plastic balloons in the same manner as the optical systems. If so an added complete list of investigations will be suggested.

Schwarzschild and Strong are trail blazing in an entirely new realm of astronomy and astrophysics—from above the atmosphere. Good results are certain to become infectious. Other investigators are destined to follow their lead and join them to exploit this exciting new tool with the promise of a crystal clear look at the exposed heavens above.

Acknowledgments

In addition to Dr. Jean Piccard, whose influence has been profound, and the investigators named above there are a number of others who have helped, either directly or indirectly, initiate the program of plastic balloon astronomy discussed. These include Dr. S. Silverman, Dr. S. G. Reed, CDR G. W. Hoover, USN, Mr. F. Isakson, Mr. G. Lill, and Miss J. Streeter, Office of Naval Research; Dr. Lyman Spitzer, Princeton University; Dr. J. Evans, Upper Air Research Observatory, AFCRC; Mr. J. McClellan, Johns Hopkins University; LCDR M. L. Lewis, USN (Ret) and Mr. O. C. Winzen, Winzen Research, Inc.; Mr. D. Church and Mr. Harold Froehlich, Mechanical Division of General Mills, Inc.; Mr. C. B. Moore, Arthur D. Little, Inc.; Mr. J. G. Vaeth, Navy Training Devices Center; and Dr. V. E. Suomi, University of Wisconsin.

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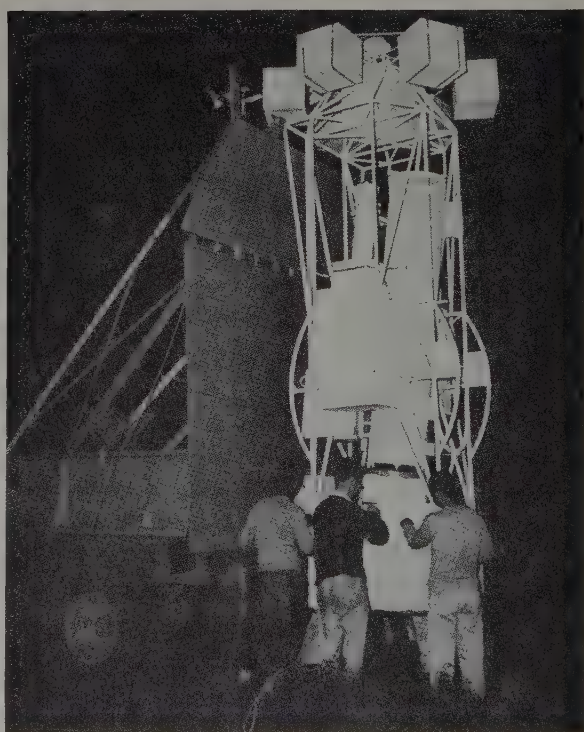

Fig. 8

FIG. 9

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Fundamentals of Inertial Guidance and Navigation

(*Continued from page 4*)

probably best be accomplished by optical and radio or radar means. This information will then permit the computation of orbits and trajectories and, in conjunction with an accelerometer system to measure the effect of thrust, will permit the changing of orbits. It is clear that complicated computations will be required and a general-purpose digital computer will probably be a standard item of equipment on space craft.

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Space Cabin Design*

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The range of requirements for adequate space cabin design is very broad indeed. For short penetration flights into nearby space, or even for short-time orbital flight, a suitable cabin might be little more than an adequately sealed and provisioned improvement of a high performance aircraft cockpit. As the time of continuous space operation increases, the cabin requirements approach those of a biologically and chemically balanced earth environment greater than a typical small earth city. These requirements clearly vary directly with the time of flight and the cumulative exposure to space environment.

To link adequately the thinking brain of a human operator to the automatic environment and operational control systems of an advanced space vehicle will require careful consideration of an overall man-machine complex such as is shown in Fig. 1.

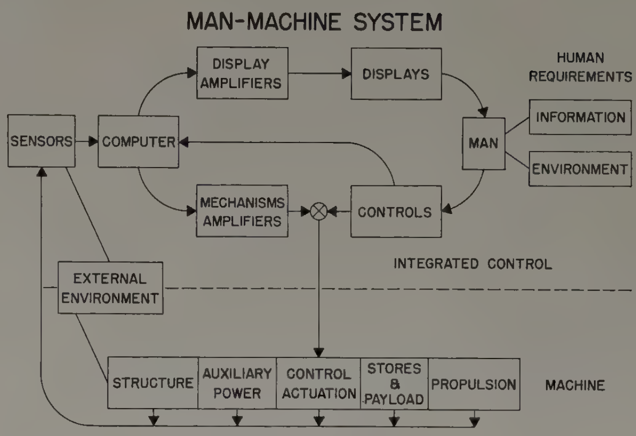

FIG. 1. Man-Machine System

In such a system the known capabilities and limitations of the human operator are accepted as the foundation on which the mechanism is built.

A set of well defined sensors detect all of the information needed for environment control, flight control and pilot display. Some of the data must be sensed from great distances to allow time for human decisions. All of the information from these sensors is fed into a central control computer. The computer configures the sensed data as a function of time into suitable forms to provide signals to amplifier systems for all of the automatic control functions and at the same time provides signals designed to give the operator an integrated display of his total operational and safety situation. Such a central computer might be divided into identical halves to provide controlled redundancy and added reliability in much the same manner as the human brain.

Through his displays the operator is provided with information to allow him to select different auto-control functions or programs as dictated by unexpected changes in the operational situation. A number of automatic programs can be made available for those situations which are predicted. For unpredicted situations the operator must be provided with information and controls to allow him to make the best use of his reasoning ability and time available to set up appropriate counter functions. The man-machine system should also fulfill the function of linking the prime operator with such remote exploration and data sensing devices as are necessary to complement the space vehicle.

A substantial portion of the space vehicle structure will be configured to protect the crew and equipment from external environment. During the atmospheric take-off phase environmental requirements not greatly different from those of present day high performance aircraft will be encountered. The increase of speed during take-off occurs in parallel with a decreasing density of the atmosphere. Temperature rise and atmospheric erosion problems are encountered for a relatively short time. They are not likely to be limiting under this condition. The problem of re-entry into the atmosphere however is another thing. In craft not utilizing thrust deceleration devices, the safety of the crew will be a much greater function of the adequacy of the structure to operate at a high temperature in order that extremely large amounts of kinetic energy can be dissipated by radiation and molecular rebound. Structural configurations allowing for sweating or subliming surfaces to provide surface temperatures very substantially below the boundary layer temperatures may be further perfected to help in alleviating the severity of this problem. Deceleration and lift control will be particularly critical during an atmospheric re-entry phase in that both accelerations and surface temperatures need to be

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related to the aerodynamic function in such a manner that neither the human nor the structure tolerances are exceeded. At the same time maximum safe temperatures are necessary to insure rapid dissipation of kinetic energy.

These problems would be greatly mitigated by the availability of retro-propulsion and the power and propulsion advances necessary to provide it.

The problems of landing and take-off on bodies without atmosphere will certainly depend on the development of precisely controlled and readily available retro-propulsive systems since other known re-entry means utilize the accelerating and lifting effects of the atmosphere itself.

As occupied space craft move outside of the atmosphere shield first solar and then extra solar system radiations will require both added study and consideration. From presently available knowledge it appears that solar energy levels of direct ultra-violet radiations are sufficiently high to cause serious burns quickly to unprotected skin. Fortunately the shielding necessary to protect against probably encountered levels of ultra-violet radiation is very small. Likewise reasonably small amounts of readily available shielding materials should take care of the expected intensities of solar x-rays and in fact most of the solar radiations at intensity levels in the vicinity of the earth. Increasing radiation intensities will limit practical approach distances to the sun or stars. Heavy ionizing rays or particles of solar or cosmic origin are quite another problem. Mass shielding appears to be impractically heavy. Experiments have already shown that ionization from heavy cosmic particles is still on the increase after the particles have penetrated one foot of lead.[1] No known practical approach toward magnetic or other means of deflecting these high-energy particles is available. The most promising course appears to be that of relying on statistical evidence indicating increased probability that the human body will tolerate probable intensities (Fig. 2) provided that ionization is not too greatly increased by the unwise use of heavy structures in the vicinity of occupied compartments of the space vehicle. It has been postulated incidentally by Dr. Fred Singer that hydrogen because of its low secondary emission would be an ideal shielding material against high energy particles. Unfortunately there appears to be a dirth of proposals dealing with practical means of bringing to bear extremely large masses of hydrogen into a practical shielding configuration.

In the event a future space vehicle approached the vicinity of masses recently discovered by radio astronomy, it is possible that high enough intensities of radio frequency energy might be encountered to approximate the effects obtained by diathermy on living tissues. In even lower frequencies, high levels of energy could produce the well known induction heating effects in conductors. In short, where the energy levels become very high, much more study is needed over a very wide range of the electro magnetic spectrum.

Meteors and Space Debris

The pitting, temperature rise and penetrating effects of meteor particles and other debris in space appears to be a problem of increasing importance as new count data become available from the astronomers.[2, 3] Newer data show greater numbers particularly in the very small particle sizes. It would appear that the structure of the space cabin might be determined to a substantial degree as a function of the requirement to resist the largest practical meteor particles and to be compatible with automatic sealing against penetration of the smaller particles (perhaps utilizing principles not too different from the self-sealing fuel tank) and of being readily repaired in event of the larger size meteor penetration. Fig. 3, which was derived from estimates of Whipple, illustrates the possible intensities and penetration data for meteors. Haber[4] has computed that excessive space craft structural temperatures might result from the energy transfer from estimated intensities of very small meteoric particles at about $\frac{1}{7}$ the speed of light. This temperature rise also would be associated with a degree of surface erosion requiring direct engi-

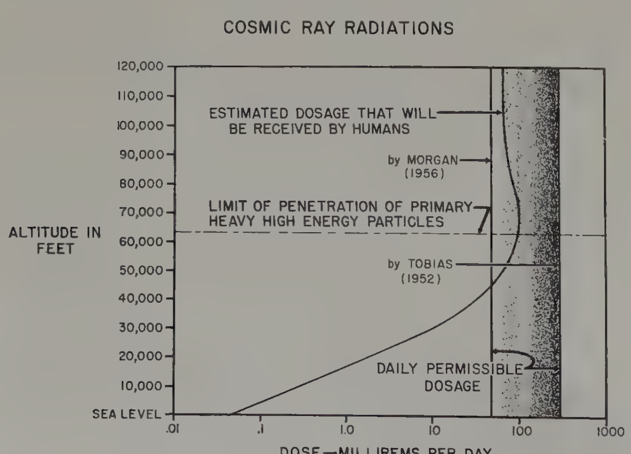

Fig. 2. Cosmic Ray Radiations

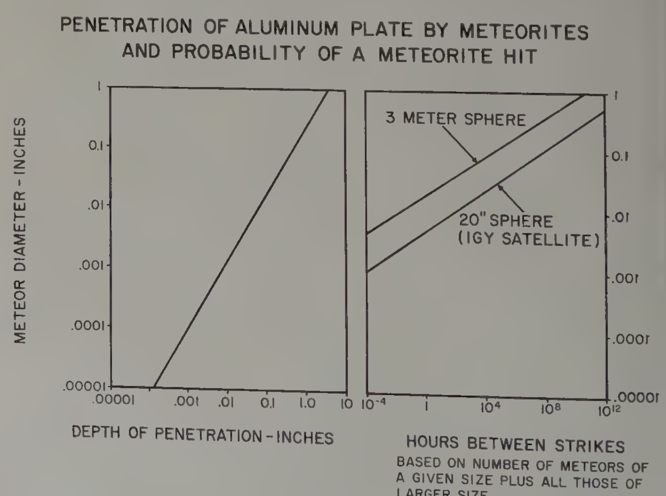

Fig. 3. Penetration of Aluminum Plate by Meteorites and Probability of a Meteorite Hit.

eering consideration. The structure for a cabin meeting hese requirements would include high surface tempera-ure resistance together with either multiple surfaces o cause the explosion and consequently increased area or dissipation of particle energy or of a low density naterial which would combine these temperature esistant properties in such a manner as to allow an xploding particle to react with a substantial mass of tructural material by virtue of its increased thickness long the path of the meteor particle.

Data already available indicate that it would be xtremely hazardous to operate either a satellite or free pace vehicle in the so-called meteor shower regions. For this reason the term "meteorology" which orig-nally was derived from the atmosphere might be xpanded further into space. The science of predicting and the means of avoiding high concentrations of neteor particles and space debris will need to become highly developed. It seems likely in fact that an earth satellite if it operates for a substantial length of time will be met with the requirement of maneuvering to avoid already known and plotted meteor showers resulting from comets and other known astronautical phenomena.

Internal Environment

Requirements for the internal environment of the space craft for long term flight will dictate the inclusion of comprehensive control equipment to insure proper air composition including such factors as the correct partial pressure of oxygen, the reduction of carbon dioxide to suitably low levels and the control of odors and secondary gases. Even the inert gaseous compo-nents such as nitrogen or helium will require suitable monitoring and control systems. Such requirements imply not only the need for continuous regeneration but also substantial storage probably in the form of chemical compounds of the vital gas to provide for emergency pressurization and damage control. A substantial part of the structural requirement of the space craft will be a function of the necessity of providing reliable pressure control. Hermetic seals will be only one portion of the pressure control requirement. The very rapid detection and sealing of all leaks will be a vital necessity. In this regard it is evident that a system of compartmentation under continuous automatic control must be provided to seal-off damaged sections temporarily. Pressurized garments or highly flexible space repair vehicles will be needed together with suitable air locks to allow the damaged compartments to be brought back into use. With sufficient storage of rapidly available vital gases, pressure might be maintained over a long enough time in a not too severely damaged compartment to allow for either the donning of emergency equipment or escape into air locks.

The substantial insulation and temperature control problems associated with atmospheric take-off and re-entry have been widely studied. Adequate radiation

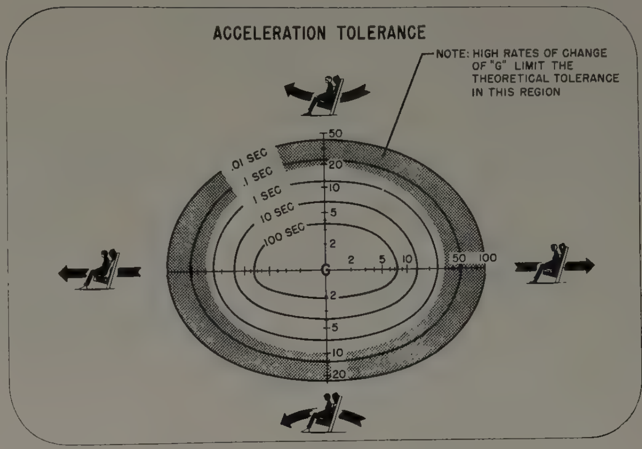

Fig. 4. Acceleration Tolerance

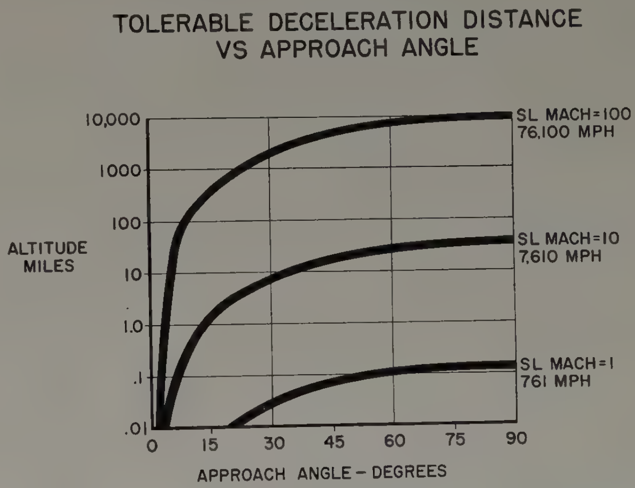

Fig. 5. Tolerable Deceleration Distance vs. Approach angle.

cycle refrigeration and heating systems utilizing a radiation surface as the final heat sink appear to be practical. The radiation surfaces could be oriented to prevent excessive heat inputs from the Sun or nearby stars. Even so, major developments together with many detailed research projects will be needed to achieve the necessary high level of reliability.

Substantial data are available indicating practical values of acceleration versus time tolerances for the human being. Fig. 4. Techniques are also available for evaluating certain of the effects of high rates of change of acceleration.[5] Fig. 5 illustrates minimum stopping distances based on human acceleration tolerances. Much less information, however, is available, con-cerning the physiological and psychological effects of prolonged reduced g or weightlessness. From the standpoint of predictable human behavior, it might be desirable to develop power and propulsion systems capable of providing the space craft with a 1 g accelera-tion or deceleration through its entire flight regime. At any rate the need for providing substantial levels of artificial gravity in order to make best use of man's earth developed capabilities appears to be highly desirable.

Major noise and vibration problems could be encountered as a result of rough operation or malfunction of high powered propulsion systems. Because of hypersonic speeds and lack of atmosphere for sound transfer, it appears unlikely that externally developed noises will be a serious problem. It is likely however that problems from the normal run of annoying sounds of internal operation and equipment will need to be met and solved.

The problems of both general and detail internal lighting should be capable of adequate solution on the basis of presently available knowledge and the application of coming new techniques.

Ecology

As the time durations of space flights increase, the problem of survival will require the combined help of practically every phase of natural science. As soon as the time of flight becomes sufficiently great to be considered continuous, the storage of food air and water and the waste provisions adequate for shorter flights will in no way solve the problem. Consideration of balanced biological systems in which food and air regeneration by cultures of living organisms or synthetic means still outside the realm of present knowledge will become an essential part of the operation. The problems of making such a system psychologically attractive will be substantial. From the biological standpoint research already under way in the Air Force School of Aviation Medicine[6] is defining the constants necessary for design of balanced biological systems. Schematically such a system might be as indicated in Figures 6 and 7. Advances in the capability of generating light with low heat dissipation could make extremely compact systems of this type practical. The problems associated with automatic control of temperatures in the cycle, with the elimination of unwanted bacteria or other growth and with the automatic cleaning and protective cycles, will require extensive research and development projects.

Just as in present aircraft the physiology of the human operator will be a primary factor in determining the design of control stations and of minimal or critical space areas. On long flights however the psychological requirements of the human being together with the provision of satisfactory living space and recreational systems will assume major importance in dictating total size.

As the time duration of manned space flight increases an increasing proportion of the total system effort will be needed to make possible the survival and effective functioning of the human operators. Practically every branch of natural science will need to contribute to the adequate solution of these problems.

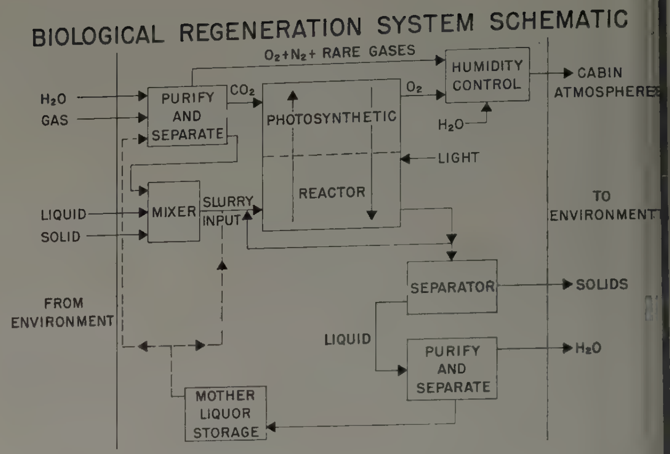

Fig. 6. Biological Regeneration System Schematic

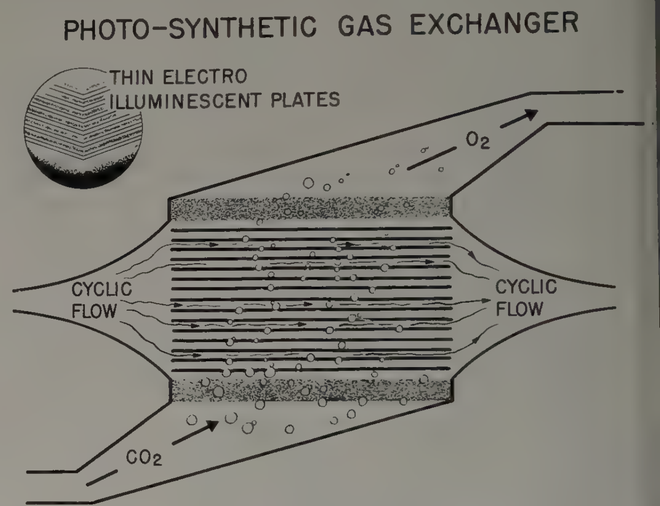

Fig. 7. Photo-Synthetic Gas Exchanger

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A Survey of Propulsion and Space Dynamics*†

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This paper briefly presents some of the factors influencing the design of space vehicles. It provides some background for this session on space vehicle design.

The design of a space vehicle is naturally governed by its mission. The combination of space dynamics and available propulsion is the dominating design factor since it determines the operational feasibility of a given mission. The concept of space stations is, for example, merely a proposed method imposed by the inadequacy of propulsion devices. There would be no reason for an orbiting space station as the take-off point for flights into the solar system if unlimited propulsion were available in practical packages. With unlimited propulsion, a flight might just as well start from the earth.

Man's development of means for travel on land and sea has led to mechanical systems producing constant dependable propulsive forces. Air travel has followed a similar development; it has been particularly adapted to its unique environment.

It is not unlikely that some of today's space-ship proposals are the equivalent of man's early concepts of airplanes propelled by paddles, sails or other ingenious, if sometimes weird, means. Let us now look at the progress that has been made and where our current thinking might lead us.

The development of propulsive systems for space flights can be shown in relation to three steps in the growth of our missile and rocket knowledge: boosted flight only, boosted flight with relatively small auxiliary propulsive means and boosted flight with sustained or intermittent in-flight power.

The ballistic vehicle is typical of the first type. In this case, the vehicle is boosted to some predetermined set of conditions (altitude, velocity and attitude) and then coasts under the influence of gravity, through a ballistic path, to its destination. This is our first step in space flight techniques. The propulsive requirements are established by the payload and mission. The accuracy of such a vehicle in reaching its destination depends upon the ability to achieve the desired conditions at the end of powered flight. While the boost-only

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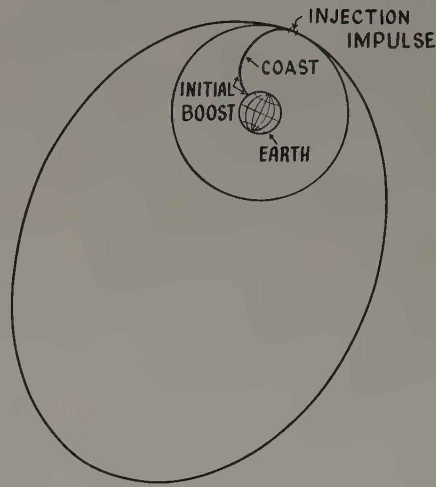


Fig. 1. Satellite Launch Program

vehicle is capable of space flights as a manned space ship, it has no means for landing and taking off from another planet. Considering this and the accuracy requirements for manned satellites, the greatest possibilities for boost-only vehicles appear to be in the field of unmanned rockets and primary propulsion systems for the next generation of aircraft, the hypersonic glider. In the development of the boost-only vehicles, chemical propellants have gone up in specific impulse (pounds of thrust per propellant flow rate, lb/sec) from approximately 200 in 1952 to nearly 300 today. Thrust levels are being pushed toward one million pounds. These changes are reflected as an increase in effective launching velocity $\left(V_L = \left[g_R R\left(1 + \frac{h}{R+h}\right)\right]^{\frac{1}{2}}\right)$ from the 5,000 fps of the V-2 in 1947 to the 23,000 fps of current ballistic vehicles.

The next step in space-flight technology is the manned satellite, a vehicle boosted to approximately 90% of orbital velocity, followed by a coast-to-orbital altitude and final propulsive force injection into orbit. This last propulsive element would provide the accuracy necessary for successful manned satellites. Figure 1 presents a schematic of such a launch program. The resultant orbit, circular or elliptical, depends upon the accuracy of injection. Figure 2 (from Ref. 3) indicates the effects of errors in velocity and flight-path angle.

Jensen (Ref. 2) has shown that for a 300-n mi orbit, an error in velocity of +100 fps moves the first apogee out 60 n mi, and an error of −100 fps moves the first perigee in 60 n mi. Likewise, a 1-deg error in injection angle would produce an error of +65 n mi in the apogee and −65 n mi in the perigee. Summerfield (Ref. 3) indicates that in order to allow for reasonable errors in propulsion system impulse and injection angle guidance, a good design will provide at least 500 to 1000 fps of velocity increment above the minimum requirements for orbital injection. Since the boost requirements of a satellite are only about 15% greater than those of typical ICBM's, it appears that a manned satellite vehicle could be based upon existing systems.

A vehicle of this type would be capable of landing on the moon from highly eccentric orbits and, with sufficient payload, returning to the earth. Figure 3 presents a family of trajectories including flight about the moon and escape. The different velocity requirements are noted for each trajectory.

Figure 4 indicates a typical trajectory for impact with the moon. Our studies show that for a lunar impact trajectory, both flight path angle and velocity magnitude at cutoff must be closely controlled. For cutoff velocities in the neighborhood of escape velocity, the allowable angular tolerance is a few tenths of a degree, whereas the velocity tolerance is about 100 fps. For the minimum cutoff velocity, about 99% of escape velocity, the allowable angular tolerance is several degrees, but the velocity tolerance is measured in a few feet per second.

For exploratory, non-impacting flights in the neighborhood of the moon, it is important to study the trajectories of moon "misses." Figure 5 presents typical flight-path disturbances due to lunar gravitational effects on an unpowered vehicle. The effects of the sun are omitted. Panels "a" and "b" show trajectories from cutoff conditions of velocity = 35,544 fps and cutoff attitude = 0°. Trajectory "a" was fired approximately 7 hr after trajectory "b." Trajectory "c" results from cutoff conditions of velocity = 35,553 fps and a cutoff attitude of 0°. Trajectory "d" is typical for cutoff conditions of velocity = 35,544 fps and cutoff attitude = 4°. The cutoff altitude was assumed to be 200 mi in every case. These figures demonstrate that small variations in cutoff conditions not only determine how close we can approach the moon, but they also result in radically different trajectories after missing the moon. Many of the trajectories similar to those shown in "a" and "d" lead to escape from the earth-moon system. It is therefore obvious that post-cutoff trajectory control is required for any advanced moon mission.

If a satellite of the moon is desired, a braking velocity of 2000 to 5000 fps in the vicinity of the moon is required. Landing on the moon will require additional energy expenditure equivalent to a velocity loss of about 7000 fps. A similar energy expenditure is required to leave the moon.

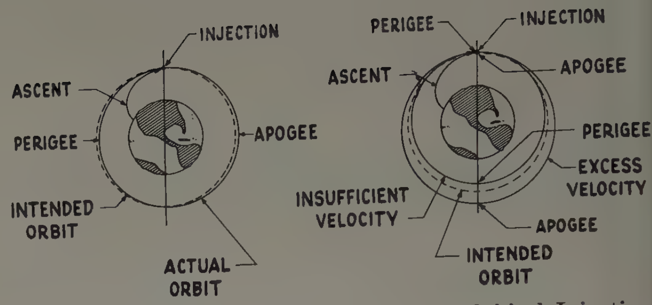


Fig. 2. Consequences of Error in Satellite Orbital Injection

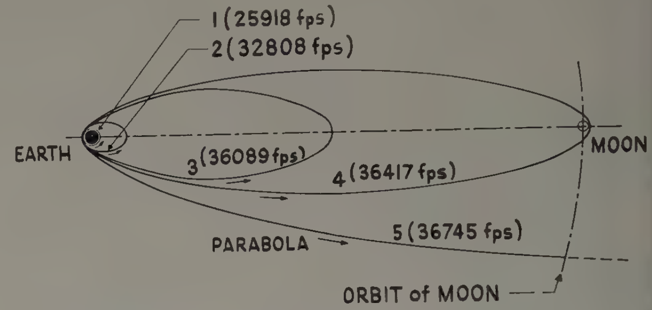


Fig. 3. Variation of the Orbit of an Artificial Satellite with Initial Velocity.

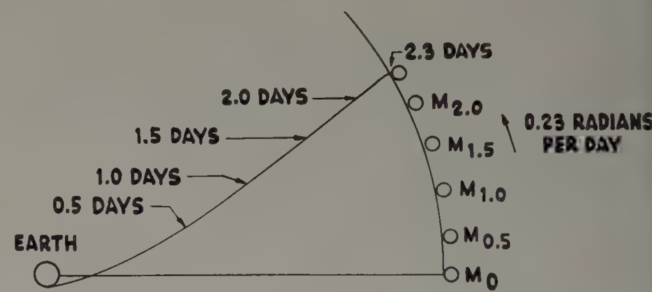


Fig. 4. Moon Rocket Trajectory as Seen from a Point Near Earth.

Considering that all of these successive thrust applications must be accurately controlled, the difficult task facing the vehicle designer can be readily appreciated.

The return of a man to earth again presents serious problems of propulsion and control. To make a safe ballistic descent from orbital paths, the vehicle must first be brought into a circular orbit. Natural decay of an elliptical orbit would accomplish this circularity. Then, the orbit must be carefully controlled to maintain circularity until the velocity drops below that required for orbiting. This procedure would result in low entrance angles (less than a degree would be desirable) and correspondingly low decelerations. Some method such as parachuting would have to be employed for landing. However, close velocity control would indicate a need for thrust. If this idea of available thrust is extended, the resulting forces could be employed throughout descent and would provide a means for landing. A lifting body would also be a means for controlling descent, but this method would greatly increase the already critical heating problems. The literature has indicated that 5° is the critical entrance angle and that an error of 300 fps over or under circular velocity at this angle could increase the de-

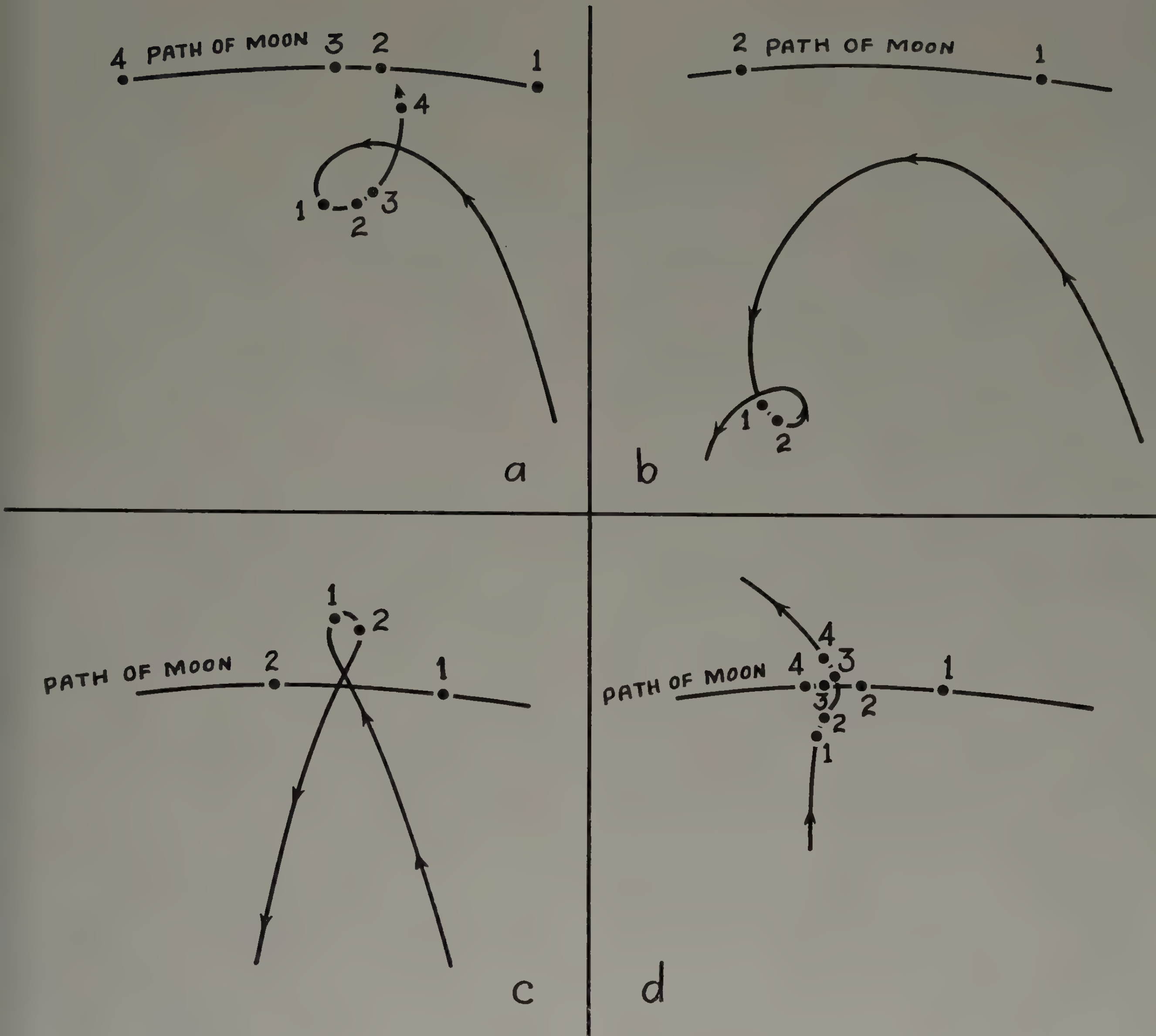


FIG. 5. Trajectories Near the Moon

celerations from 7 g to 30 g and increase skin temperatures from 2500° to 5000° F. Figure 6 ("a" and "b") indicates the effect of entrance angle and velocity on the decelerations. Figure 6 "c" presents the acceleration time history for vertical re-entry from an initial altitude of 1800 mi and with a ballistic coefficient of 0.32.

We now arrive at the final step, the true space vehicle capable of safely and efficiently carrying man to another planet and back. First, let us consider some of the possible flight plans for various space missions. One of the more established concepts is that of building an orbiting space station with vehicles designed for both atmospheric ascent and descent providing the earth-station transit. Another vehicle designed strictly for space will provide the means of traveling from the station to another planet and back. This vehicle would carry a smaller vehicle designed for landing on the particular planet.

Another technique would be that of sending tankers along with the space vehicle. In one case, four vehicles would leave the earth and rendezvous in an earth orbit; one would be a lead vehicle, one a drone and two would be tankers. While in orbit, the lead vehicle and drone would draw fuel from the tankers and then, by elliptic paths, transfer into, say, the moon's orbit. Here a small transfer vehicle carried in the drone would be sent to the moon's surface with instruments or for manned exploration. The drone would then transfer fuel to the lead vehicle for return to earth.

Another approach would be to orbit a vehicle capable of utilizing thrust pulses to transfer from the orbit of one planet to the orbit of another. In any case, we must ensure a high probability of human recovery through short flight times and tolerable environments. Also, we must develop a combination of propulsion system and mission profile that is economically compatible with the procedure of such travel.

The first two concepts of space travel are based on a step-type flight. This concept appears more feasible

than a single step when one considers the size of a single vehicle based on current propulsion systems and designed to perform the entire mission. To pursue this point, let us consider the velocity at the end of powered flight to be expressed as: $V = I_{sp}\, g(\log_e M)$ — (drag and gravity losses) where I_{sp} is the propellant impulse (pounds of thrust per propellant flow rate, lb/sec), g is gravitational acceleration and M is the mass ratio (weight at launch/weight at burnout). Figure 7 shows the mass ratio requirements for impulses of 300 and 600. A drag and gravity loss of 1300 fps has been assumed. A single space vehicle with a propellant impulse of 300 capable of landing on and taking off from the moon (14,000 fps additional velocity increment) would require a mass ratio of more than 150. If we retain the single-step concept, but stage the vehicle to take advantage of improved stage mass ratios and velocity increments, the mission would still require a very large three- or four-stage rocket.

The question then arises: How far are we from chemical propellant impulses of 600 or better? Liquid propellants now have specific impulses near 300, and, with such combinations as fluorine and hydrogen, propellant impulse could increase to between 370 and 400. Theoretical works for free radical propellants have indicated specific impulses of 400 to 1300; however, a practical free radical propulsive system is yet to be developed. Propellant stability is a big stumbling block to free radical propulsion development. Another problem is the combustion chamber material temperature limits, which currently restrict free radical propellant impulses to 600. However, a system of this capability could power a single-step moon-landing vehicle at the more reasonable mass ratio of 13.5.

Another possible type of propellant system is the nuclear reactor and light gas system, where reactors would supply energy to heat and expand a gas, possibly pure hydrogen, for propulsive energy. Here, heat and shielding problems appear to be the stumbling blocks to development. The current permissible operating temperatures limit the propellant impulse to 600, which is no better than the best outlook for chemical propellants, yet the weight penalty is much greater. Thus, it appears that nuclear systems will be used primarily as electrical power sources for more advanced systems.

The more advanced systems include the use of solar energy focused by large reflectors to heat and expand a light gas, as with the nuclear power plant, and the use of electric arc heating for the acceleration of a plasma of atoms, molecules and ions. Both systems are gas-heating systems and are limited in duration of application by the gas storage capability of the vehicle. The solar energy system is further highly susceptible to meteorite damage. The arc-heating system yields no greater exhaust velocities than a nuclear system and is far more complex. Consequently, neither of these systems is a significant advancement over the nuclear power plant. Therefore, let us concentrate on

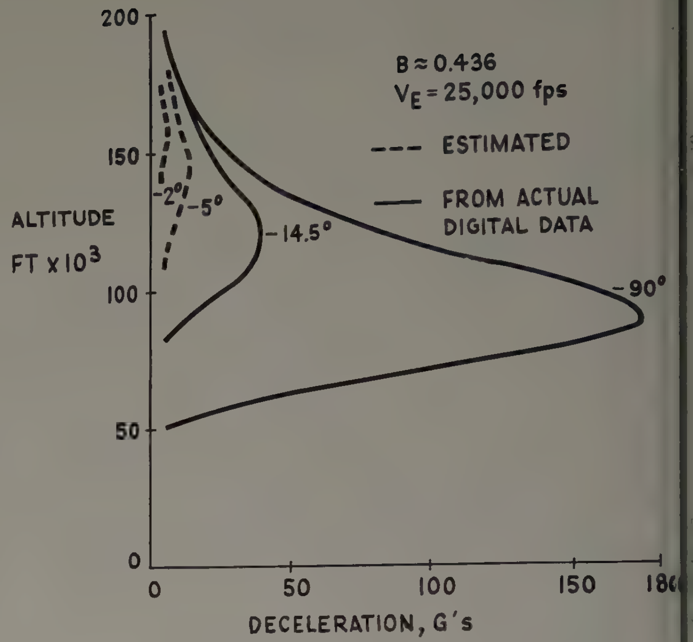


Fig. 6a. Effect of Entrance Angle on Decelerations

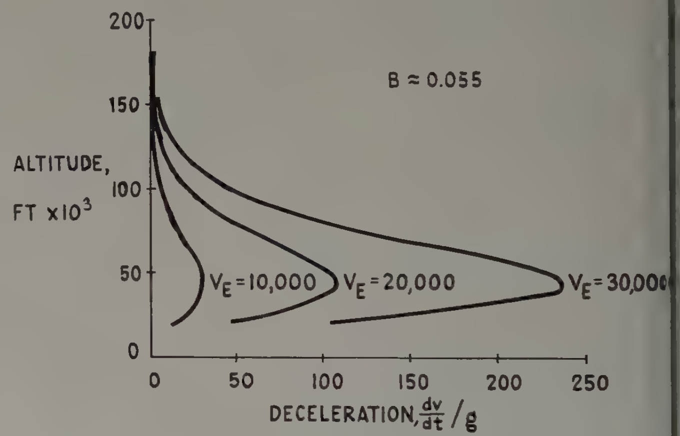


Fig. 6b. Decelerations for Typical Vertical Re-Entries

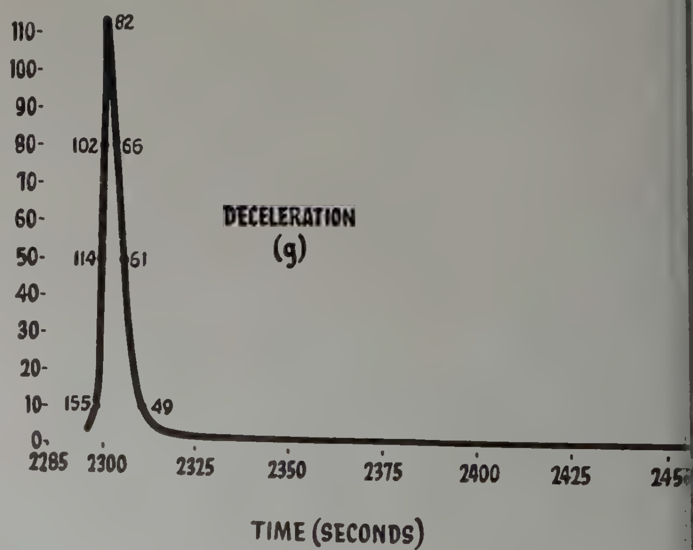


Fig. 6c. Re-entry Deceleration—Nominal Performance

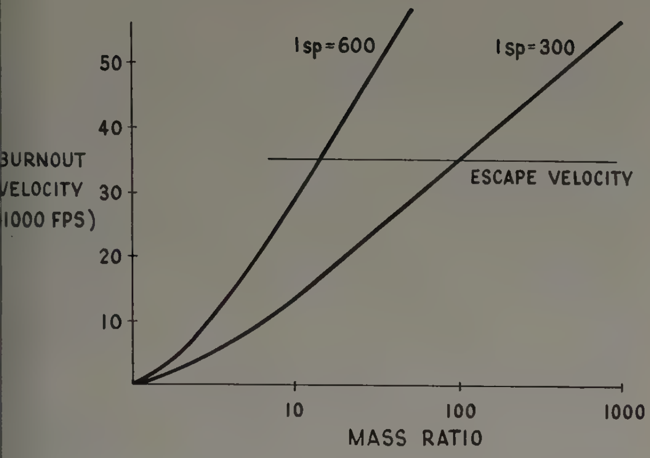


FIG. 7. Mass Ratio Requirements vs Burnout Velocity

the truly advanced systems, ion propulsion and photon propulsion. The theory of the first is understood, but no workable propulsion equipment has been demonstrated. The theory of photon propulsion is debated.

In the ion propulsion system, a propellant material such as cesium is ionized and subjected to electrical fields, where the particles are accelerated to very high velocities and exhausted from the vehicle. The power for the electric field could be supplied by a nuclear reactor. In this case, vehicle accelerations would be small, 0.01 g to 0.001 g, but could be sustained throughout flight. The rocket power and mass increase as the square of the exhaust velocity. The thrust, however, increases only with the first power of the exhaust velocity. Therefore, a practical limit exists for such a system.

According to Stuhlinger (Ref. 18), a typical ion-propelled vehicle for traveling to Mars and back would carry a 150-ton payload and would take off at 730 tons. The propellant would weigh 365 tons, and a total electrical power production of 23,000 kilowatts would be needed. The propulsion system would work throughout the entire trip and would produce accelerations of 10^{-4} g. The voyage would take approximately 400 days one way. The techniques for building such a vehicle are known today.

The photon rocket is completely theoretical and would employ light as a means of propulsion. The theory assumes that light is made up of quanta of energy known as photons. This energy has mass and can be used to trasmit momentum to a vehicle through radiation. A propulsion system of this type would develop 1- to 2-g accelerations.

The optimum space-vehicle design would incorporate the best propulsion system and a programmed flight path to obtain maximum distance at minimum take-off weight. Because of the small accelerations of the advanced systems, a chemically propelled booster would be required to launch the vehicle out of the earth's atmosphere. A summary of all the various propulsion systems and their capabilities gathered from various sources appears in Table I.

With these propellant systems in mind, let us look again at a single-step mission. Assume the vehicle is

TABLE I

Propellant	Accelerations (g)	Exhaust Velocity (m/sec.)	I_{sp}
Chemical..........	1–8	3000	300–380
Atomic Radicals....	1–8	—	400–1300
Nuclear or Solar....	0.01	4000–6000	400–800
Nuclear + Ions.....	0.0001	100,000	800–1500
Photon............	1–2	300,000,000	30,500,000

boosted into an orbit of the earth, from which it will transfer to the orbit of the target planet. Tsien (Ref. 13) has shown that radial thrust force applications are less efficient for escape than tangential thrust applications. Figure 8 presents the difference between transfer of orbits by chemical pulse and by constant thrust means for a trip to Mars. The chemical rocket thrust is applied as an impulse tangent to the initial orbit, resulting in escape from the earth and subsequently an elliptic coasting transfer trajectory, where the rocket is under the influence of the sun alone. On arrival in the new orbit, a thrust pulse of a decelerating nature is applied tangent to the new orbit. Small thrust pulses along the way would provide navigational correction. This is a minimum energy orbital transfer. It can be seen that constant thrust produces shorter flight times.

Figure 8 shows various flight paths from the earth to Mars. A minimum energy trajectory gives a flight time of about 260 days. Contrasted to this flight time are those for continuous thrust flights ranging from 2 days for 1-g thrust to about 21 days for 10-mg thrust.

Dandridge Cole (Ref. 17) has also calculated flight times for continuous-thrust earth-moon trips where travel is over a radial path. Average boost accelerations of 2 g for a moon vehicle of 100 tons would result in a 3 hr 15 min trip. The voyage would require the equivalent of 27.9×10^{13} ft lb, or the energy of 8.6 lb of deuterium in a fusion reactor. If a chemical rocket were to leave the earth with escape velocity, the trip

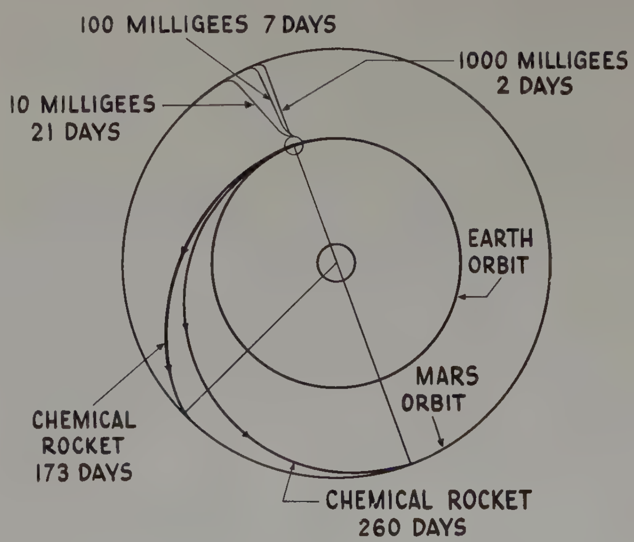
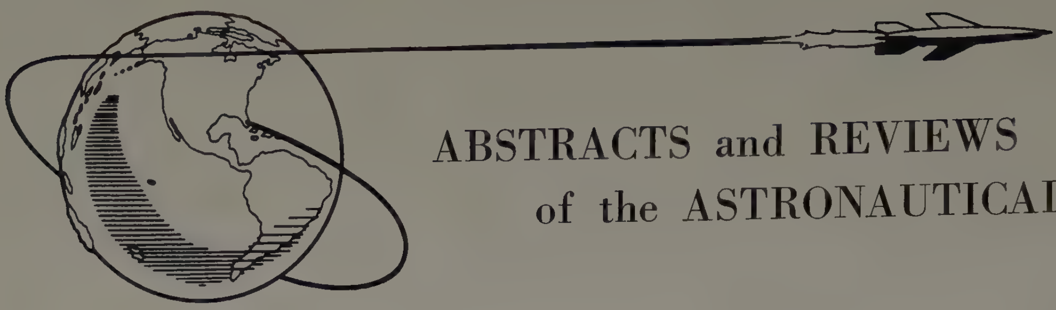


FIG. 8. Constant Thrust Brachistochrones vs Chemical Rockets.

(Continued on page 30)



ABSTRACTS and REVIEWS of the ASTRONAUTICAL SCIENCES*

The *Journal of Astronautical Sciences* presents literature from all of the major technical fields composing the astronautical sciences. Reviewed in the Abstracts and Review Section are scientific, technical and research publications presented in this country, as well as from member societies of the International Astronautical Federation. Additional papers and books presenting technical material pertinent to the astronautical sciences are reviewed from time to time in this Section.

The subject list of technical literature appears under the following headings, as space permits each issue: Aerodynamics; Aeronautics; Astronautics-General; Astronomy; Astrophysics, Atomic and Nuclear Physics; Biology, Aviation and Space Medicine; Human Factors; Communications, Electronics, and Electrical Power Generation; Guidance, Control and Navigation; Heat Transfer and Fluid Flow; Materials, Structures, and Vehicle Design; Meteorology and Aerophysics; Propellants, and Propulsion; Space Flight Mechanics; and Theoretical Physics.

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Aerodynamics

(1) *Supersonic Flow about Blunt Bodies of Revolution*, Fausto G. Gravalos, General Electric Co., Philadelphia, Pa. (AAS Preprint 57-5). A method is developed for the computation of the pressure at and of the density field around a blunt body of revolution moving at supersonic speeds. Basic assumptions are: (1) the angle of incidence is zero and (2) the fluid is in frozen equilibrium.

Three of the fundamental equations ruling the flow field, the equation of energy, the constance of entropy with time and, approximately, the equation of continuity can be written in finite terms. The fourth equation, the momentum equation along the normal to the streamlines, $\partial p/\partial n = \rho V^2/R$, brings into the computations of local conditions necessary information from downstream by taking into account the curvature $1/R$. In this manner, the flow field about the sonic line, together with the location and shape of the shock, is determined.

Once the shock shape is assumed known, the purely subsonic part of the flow field, in a relatively small region about the axis, is computed by transforming the set of differential equations, for a contour boundary value problem, into difference equations. For the purely supersonic part of the flow field, using the technique of integration along the characteristics, extensive numerical experimentation was done. All the work with γ = constant is extended to conditions at chosen equilibrium by proper analytic interpretation of the available gas tables.

Astronautics, General

(2) *Approaches to the Development of Space Vehicles*, George W. Hoover, Cmdr., USN, Office of Naval Research, Washington, D. C. (AAS Preprint 57-29). This paper discusses logical approaches to the problem of establishing the requirements for space-ship systems. It discusses the statement of problems in fundamental terms in order to seek out ultimate rather than partial solutions.

Astronomy

(3) *Considerations about Visibility of Satellites for the Unaided Eye*, Ingeborg Schmidt, Division of Optometry, Indiana University, Bloomington, Ind. (AAS Preprint 57-36). In order to draw conclusions about the visibility of satellites a suggestion is made to compute spaces of potential visibility for different positions of the sun below the horizon. Difficulties encountered are discussed.

(4) *A Preliminary Determination of the Position of Some First- and Second-Magnitude Stars on Mars' Celestial Sphere*, Frederick R. West, Jr., Avco Mfg. Co., Lawrence, Mass. (AAS Preprint 57-44). A knowledge of Mars' celestial sphere is necessary both for the successful placing of an unmanned space ship in a specific orbit around Mars, and also for surface exploration. This knowledge will aid surface explorers in finding their course across the planet and will help them to map certain parts of the planet more accurately. By use of spherical trigonometry and astronomical data the position of Mars' north celestial pole is calculated to within 15 minutes of arc. The declination and right ascension of the pole are 53 52′ N and 319 23′, respectively. Using tabulated star positions, the aerocentric declination and right ascension from the Martian vernal equinox are found for some first- and second-magnitude stars. An example of the possible use of these data in locating the position of an exploring party on the planet's surface is included.

Astrophysics, Atomic and Nuclear Physics

(5) *A Recoverable Emulsion Package for Extra-Atmospheric Study of Cosmic Rays*, Robert A. Webster, Advanced

* All abstracts included in this issue of the *Journal* cover technical papers presented at the AAS Fourth Annual Meeting held at the Engineering Societies Building, New York City, January 29 to 31, 1958. Preprints of these papers are available at 50 cents (25 cents for AAS members). In ordering, please quote the AAS Preprint number.

Proceedings of the Fourth Annual Meeting will be available by about April 15, 1958; the price will be $8.00 ($5.00 for AAS members).

Design Dept., The Martin Company, Baltimore, Md. (AAS Preprint 57-32). This paper describes an extra-atmospheric recoverable cosmic-ray emulsion package developed by The Martin Company. The package contains 50 pounds of nuclear emulsion plates which could be carried beyond the atmosphere by a three-stage rocket vehicle. These emulsion plates would be exposed to cosmic radiation for significant time periods and then recovered safely. The three stages of the rocket would be fired consecutively in a near-vertical trajectory. The third-stage motor would be separated from the emulsion package at burnout, the package would coast to the trajectory apex, and then descend to the earth's surface under the acceleration of gravity. Final recovery would be effected by a landing parachute to be opened at approximately 10,000 feet. The package could be located by homing on a transmitting radio beacon carried in the package. The cosmic-ray package is designed to withstand the aerodynamic heating and deceleration experienced during re-entry and also to withstand the shock of landing in water.

Biology, Aviation and Space Medicine, Human Factors

(6) *Advances in Astro Biology*, Hubertus O. Strughold, School of Aviation Medicine, Randolph Field, Texas. (AAS Preprint 57-15). Astrobiology deals essentially with the problem of the possibility of indigenous life on other planets. This paper discusses these possibilities in our solar system based on a zonal ecological approach, and finally concentrates upon the planet Mars by reviewing recent spectrographic studies and other studies concerning the behavior of terrestrial microorganisms under simulated Martian conditions.

(7) *The Selection and Training of a Bio-Satellite Crew*, D. W. Conover, E. G. Aiken, and C. M. Whitlock, Convair, San Diego, Calif. (AAS Preprint 57-16). The success of the data-gathering phase of the first manned flight in space will rest to a considerable degree upon the individual characteristics of the man chosen to make the trip. This paper describes the sort of selection and training program which will be required if these "factors of the individual" are to act in the direction of increasing rather than decreasing the venture's probability of success. For the purpose of this presentation it is assumed that the crew will be restricted to one person and the length of the flight to under ten days.

The proposition that psychological stresses will exceed physiological stresses during the first flight is developed and a rigorous stress indoctrination program is suggested as a means of reducing anxiety about the unknown. Because the training and indoctrination program is considered to be very strenuous and taxing, it will probably serve to reduce further the size of the crew group. The levels of training will consist of elaborate simulations in an omni-environmental centrifuge of the physical conditions (except for weightlessness) which are expected during the flight. Certain aspects of weightlessness can be simulated through submergence techniques and additional indoctrination can be provided by ballistic flights in a high-performance aircraft.

The training program will also involve physical and psychological conditioning and detailed practice on equipments which the individual will be expected to operate. Much of the discussion on training is based on adapting past techniques in aviation and elsewhere to the peculiar requirements of space flight. The problem is also examined in the light of its socio-psychological implications for the immediate future and suggestions for equipment design are presented.

(8) *Orientation of Research Needs Associated with Environment of Closed Spaces*, William T. Ingram, College of Engineering, New York University, New York, N. Y. (AAS Preprint 57-17). A study of several aspects of the environment of closed space has provided a basis for orientation of research needs in coping with the requirements of a healthful, safe, working space under a closed ecology.

A discussion of present knowledge and work on such essentials as CO_2–O_2 conversion, treatment of bodily wastes, recovery of usable water from contained air, urine, and other sources, removal of pollutants from contained air, purification or disposal of various liquid wastes is offered here.

The problems of closed-space ecology may be divided into those occurring during extra-terrestrial flight (1) of short duration, amounting to hours, (2) of intermediate duration, amounting to days, and (3) of long term, amounting to weeks and months. This discussion deals almost entirely with the third problem, but the orientation of research need emphasizes that careful study should be made of factors affecting weight and volume of equipment required to process and maintain an environment with total conservation of mass balance and recycle of matter, as opposed to the principle of replacement of essentials such as oxygen and water by withdrawal from storage while polluted matter is ejected from the closed system environment. For conditions introduced by flight of short or intermediate duration, engineering economics may justify provision for partial or even total replacement of environmental constituents. Long-term operations seem impractical without plans for cyclic use of the contained matter. Re-use of contained matter demands positive mechanical, chemical, or biological action that has no chance of failure, since the closed environment will be totally dependent on the continuous and proper functioning of reclamation and conversion operations.

(9) *Ionization Dosage from X- and Beta Rays in Flight through Auroral Displays*, Herman J. Schaefer, School of Aviation Medicine, Naval Air Station, Pensacola, Fla. (AAS Preprint 57-18). The earth's magnetic field exerts a deflecting influence on charged cosmic-ray primaries prohibiting low-energy particles from reaching the planet's atmosphere. Therefore, one would expect to encounter low-energy particles only in deeper regions of the air ocean, after they have been slowed down in interaction processes, or at any altitude around the geomagnetic poles, since charged particles moving in the lines of magnetic force are not deflected.

In rockoon experiments, Van Allen and collaborators have found, a low-energy ionizing radiation of high intensity in the latitude belt between 60° and 80° at altitudes of 80 to 100 kilometers. This latitude belt very nearly coincides with the region to which aurorae are limited.

Filter analysis identifies the radiation as x- and beta rays of 10 to 100 kv energy range. Conversion of the recorded photon and electron intensities into tissue ionization in rad-units leads to a dose which is about 1000-times larger than that of the ordinary cosmic-ray beam at the same altitude and latitude. However, since the phenomenon seems limited to a latitude range of about 20°, vehicles traveling in ballistic trajectories or satellite orbits will traverse the critical region in a few minutes exposing their payload to only a small fraction of the 24-hour dose of about 10 rad.

The absorption characteristic of the radiation will be briefly discussed in its implications for the attenuation in air-frame and space-suit materials.

(10) *Five Days Aloft: Research in Human Travel on the Endless Frontier of Time*, Charles A. Dempsey BSID, Franklin D. Van Wart, Capt. USAF, Leonard Eisen, Lt. USAF, John G. Roth, Capt. USAF (MC), Nina K. Morrison, Capt. USAF, Charles Myers BSID, Aero Medical Laboratory, Wright Air Development Center, Dayton, Ohio. (AAS Preprint 57-19). This paper is devoted to habitation research, which investigates the diverse parameters of protracted

advanced human travel. Preliminary conclusions indicate that a simulated 120-hour journey does not produce significant changes in human effectiveness, or the living patterns of man while enclosed in an artificial habitat. Scientific knowledge from this research effort will contribute to the formulation of future requirements to facilitate the evolution of a harmonious ecology for space travel.

A research film "Flight to Nowhere" (prepared by the WADC Aero Medical Laboratory) depicting the comprehensive factors of man in a space-equivalent habitat, was shown for the first time.

(11) *Synthesis of Human-Automatic Control Systems for High-Performance Vehicles,* William L. Morris, Autonetics Division and Richard C. Kaehler, Los Angeles Division, North American Aviation, Inc., Los Angeles, Calif. (AAS Preprint 57-20). This paper gives a summary of tests conducted at North American Aviation, Inc. utilizing analogical computer simulation methods and simulation by specially equipped aircraft in order to attain optimum integration of human pilots with automatic control systems for high-performance vehicles. The discussion includes a description of missile systems, simulation methods and equipment, test procedures, results, and applications to space systems.

A short motion-picture sound film was shown.

(12) *Isolation and Confinement in Space Flight,* G. E. Ruff, Capt., USAF (MC), E. Z. Levy, Capt., USAF (MC), and V. H. Thaler, Capt., USAF (MC), Aero Medical Laboratory, Wright Air Development Center, Dayton, Ohio. (AAS Preprint 57-21). Crews of space vehicles will function in environments involving drastic alterations in normal patterns of sensation. Studies are discussed which suggest that stresses arising from sensory changes, isolation, and confinement may disrupt human performance. Present experiments in this area involve both isolating individual subjects in a darkened anechoic chamber and confining five-man groups in a small compartment for extended periods of time. Psychological, physiological, and biochemical measures are used to determine the effects of these situations. Results indicate wide variations in response by the individuals tested and permit tentative conclusions regarding methods of crew selection.

(13) *Design of an Algal Culture Chamber Adaptable to a Space Ship Cabin,* James G. Gaume, The Martin Co., Denver, Colo. (AAS Preprint 57-22). A design is proposed for an algal culture chamber suitable for adaption to a space-ship cabin, and intended as a component of a complete photosynthetic exchange system capable of effecting the balance of a sealed ecological system. Such a system would become necessary in manned space operations of a prolonged nature. Three main objectives must be met in the operation of the system: (1) gas exchange, (2) waste re-utilization, and (3) food production.

(14) *Space Cabin Design,* Alfred M. Mayo, El Segundo Div., Douglas Aircraft Co., Inc., El Segundo, Calif. (AAS Preprint 57-30). This paper outlines the various requirements which must be defined before considering the design of crew stations and quarters for space ships which operate away from earth for extended time periods. Certain problem areas and the attendant scientific disciplines necessary to their engineering definition and solution are discussed including (1) man-machine system relations, (2) protective structure and the effects of temperature radiation, meteors and space debris, (3) control of internal environment to meet human requirements, and (4) closed cycle ecology, food supply generation, cleansing, bacteriological considerations. The author closes with a plea for an integrated effort to consider total requirements for Space Cabin Design.

(15) *Hydrogen Peroxide as a Source for Oxygen, Water, Heat, and Power for Space Travel,* Noah S. Davis, Becco Chemical, Food Machinery Corp., Buffalo, N. Y. (AAS Preprint 57-31). Concentrated hydrogen peroxide is a stable high-density liquid which can be decomposed by means of a catalyst to produce pure oxygen and distilled water. During the decomposition, heat and power become available. This paper considers the use of hydrogen peroxide to produce oxygen and water and to provide heat and power for miscellaneous applications.

Communications, Electronics, and Electrical Power Generation

(16) *A Universal Radio Astronomy System for Radio Telescopes, Space Vehicle Tracking and Scatter Propagation Studies,* George J. Doundoulakis, Electronics Division, General Bronze Corp., Garden City, N. Y. (AAS Preprint 57-23). A universal adaptation of a radio telescope antenna reflector and pedestal mechanism is described which the General Bronze Corporation is manufacturing for the National Bureau of Standards. The design criteria of antenna systems will be covered for application to the problems of collecting radio astronomy data. The paper will include radiation patterns and serve control systems as well as an analysis of the overall environmental design conditions. Illustrations show actual components and measurement data taken on miniaturized systems.

(17) *Radio Propagation in Interplanetary Communication,* Allen M. Peterson, Stanford University, Palo Alto, and Stanford Research Institute, Menlo Park, Calif. (AAS Preprint 57-24). The propagation of radio waves in interplanetary space is considered in the light of recent experimental data. Attention is directed to the dominant role of radiation and particle bombardment from the sun in determining radio frequency propagation characteristics, particularly in the earth's outer atmosphere.

Radio propagation experiments based on natural and man-made radio transmissions from the earth's surface and observations of solar and cosmic radio noise provide important clues to the interplanetary communications environment. Most important among experiments based on transmissions from the earth's surface are "Whistler" mode studies at very low frequencies (VLF) and moon reflection studies in the high-frequency band (HF) and above. Radio astronomy experiments, particularly solar studies, are also a very important source of data on interplanetary propagation. The advent of earth satellites provides additional experimental techniques based on transmissions from the satellite and on radar reflections from the satellite vehicle.

(18) *Television Telemeter for Missile Test Programs,* Daniel Hochman and Jeremy P. Taylor, Telecommunications Dept., Missile Systems Division, Lockheed Aircraft Corp., Palo Alto, Calif. (AAS Preprint 57-25). It has been demonstrated in previous missile programs that pictorial information provides a particularly useful supplement to data provided through conventional telemetry channels. A study has been made on a monochrome television telemeter system to be used in testing and evaluating non-recoverable supersonic missiles. The purpose of this system is to provide pictorial information on events such as stage separation, motor ignition and burning, vehicle yaw, pitch and roll, and others, as they occur in actual flight. This paper describes a long-range medium-resolution system designed to supply video information from distances up to 1000 miles.

(19) *Data Links in Space Exploration, Their Basis, Application, and Limitations,* Henry E. Prew, Aeronautical Equipment Div., Sperry Gyroscope Co., Great Neck, N. Y. (AAS Preprint 57-26). Of equal importance to the problems of development of vehicles capable of reaching into interplanetary space are those of information interchange between the vehicle and other vehicles or planets. Data links for communication of space measurements, vehicle status,

or control information will be necessary for both scientific probing and vehicle navigation. Such links must obviously be based upon some form of electromagnetic radiation, with optical, infrared, or radio being the most likely techniques. This paper is mainly concerned with a presentation and discussion of a general method, with system design curves for establishing the system parameters for a data link for a given set of operational requirements using any of the radiation methods indicated above. The problem used as an example concerns the data link of a remotely controlled research vehicle capable of reaching Mars.

(20) *Some Observations on Russian Electronic Technology*, Charles L. Rouault, Heavy Military Electronic Equipment Dept., Defense Electronics Div., General Electric Co., Syracuse, N. Y. (AAS Preprint 57-28). In the Spring of 1957, a group of American engineers attended the annual meeting of the Popov Society in Moscow and visited electronic manufacturing facilities in the Moscow-Leningrad area. From this visit and a study of the Sputnik articles appearing in "Radio" for June, July and August, an estimate can be made of the electronic capabilities of the Russian industry. The rate of advance, and the current position indicate an overall capability of the Soviet Union generally equal to its requirements.

Guidance, Control and Navigation

(21) *Fundamentals of Inertial Guidance and Navigation*, William E. Frye, Guidance and Communications Dept., Missile Systems Division, Lockheed Aircraft Corp., Palo Alto, Calif. (AAS Preprint 57-9). Some of the basic concepts of the science of inertial navigation and guidance, including possible applications to space flight and astronautics are discussed. The principle of the Schuler pendulum and the fundamentals of accelerometers are described. The mathematical solution for hypothetical accelerometer system, consisting of three accelerometers and three gyros, which performs the same function as a Schuler pendulum, is derived. It is suggested that other possible configurations might consist of ordinary pendulums employed as accelerometers using gravity as the restoring torque. Accelerometers are practical for use in gravity-free space since they do not measure forces due to gravity.

(22) *Determination of a Unique Attitude for an Earth Satellite*, William R. Davis, Guidance and Communications Dept., Missile Systems Division, Lockheed Aircraft Corp., Palo Alto, Calif. (AAS Preprint 57-10). The existence of unique stable attitudes for a body orbiting in a central gravitational force field, such as that of the earth, is shown to depend only upon (1) the requirement that the three principal moments of inertia of the body be different, (2) the diverging nature of the gravitation field, and (3) the centrifugal-force effects of the orbital angular velocity. Both mathematical and physical models are discussed. Particular emphasis is given to the existence of unique attitude about a body axis which is maintained always collinear with the radius vector from the center of the gravitational field to the center of mass of the body.

(23) *Satellite Ascent Vehicle Guidance Requirements*, C. L. Keller, Air Armament Division, Sperry Gyroscope Co., Great Neck, N. Y. (AAS Preprint 57-11).

(24) *Inertial Navigation and Space Travel—Fundamental Principles*, C. J. Mundo and T. V. Newman, Arma Division, American Bosch Arima Corp., Garden City, N. Y. (AAS Preprint 57-12). Recent activity in the field of guided missile development has underlined the importance of automatic navigation systems. In addition, anticipated increases in the speed of manned aircraft indicate the desirability of automatic navigation techniques for this application as well. Systems which are in use or under development range from simple dead-reckoning devices utilizing magnetic heading and airspeed data as inputs, to more sophisticated systems employing Doppler radar, automatic star trackers, radio aids (Loran, etc.), and inertial navigation techniques.

Of these, only inertial navigation is free from enemy interference, the necessity for cooperative ground stations, and the vagaries of the weather. This is a result of the inherent self-contained nature of this type of navigation system, which arises from the character of its input data. This series of two papers will examine the possibility of inertial navigation for space travel.

Fundamentally, an inertial navigation system is a dead reckoning system with a very significant characteristic which differentiates it from more conventional dead-reckoning equipment. In the usual type of dead reckoning, vehicle position is determined from a single integration of the measured velocity vector (magnitude and direction). In inertial navigation, however, the vehicle is navigated by a double integration of directly measured acceleration. Now, a direct measurement of velocity for dead reckoning requires data from external observations e.g. airspeed indication, Doppler radar data, etc., while an inertial system can internally determine vehicle acceleration by measuring reaction forces sensed entirely within the airframe.

This paper deals with the following fundamental principles of inertial navigation: (1) Inertial navigation is a means of determining a vehicle's position by double integration of vehicle acceleration, (2) Accelerations due to non-gravitational forces (thrust, lift, drag, etc.) are determined by direct measurement using accelerometers, (3) Due to the principle of equivalence, it is impossible to determine accelerations due to gravitational forces by direct accelerometer readings. Therefore, gravitational accelerations must be determined by computations based on "a priori" knowledge of the gravitational field pattern together with the vehicle's computed position. This computation gives rise to a feedback loop in the inertial navigation system which has the capability of sustained oscillations (the well known Schuler oscillations), and (4) In order to maintain the accelerometer sensitive axes aligned with the proper coordinate system it is necessary to mount these components on a stabilized inertial platform which obtains its directional reference in inertial space from gyroscopes. The paper also includes a discussion of some applications of those principles to space travel.

(25) *Steering of an Ascent Rocket for Maximum Cutoff Velocity*, W. H. Foy, Jr., The Martin Co., Baltimore, Md. (AAS Preprint 57-14). The general solution to the variational problem of specifying the thrust-attitude program to maximize the cutoff velocity of an ascending rocket with a known thrust-acceleration time history is obtained in the form of a set of partial differential equations. The constraint of a specified burnout altitude is imposed. In the case of no atmosphere and an approximated gravitational force the equations can be solved analytically, and a solution is found to be a linear time-variation of the thrust-attitude angle in inertial space. The initial angle and its rate are specified in terms of the initial conditions, the cutoff time, the thrust-acceleration curve, and the cutoff altitude.

(26) *Measurement of Velocity in Space*, David Sonnabend, Systems Design Dept., Missile Systems Division, Lockheed Aircraft Corp., Palo Alto, Calif. (AAS Preprint 57-27). An instrument has been devised for measuring the instantaneous inertial velocity in space based upon Bradley's stellar aberrations. The theory is developed and the proposed instrument founded on this theory is described. The techniques used will be integrated into a complete celestial navigation scheme.

(27) *Interplanetary Applications of Automatic Navigation*, Edward V. Stearns, Guidance Dept., Missile Systems Division, Lockheed Aircraft Corp., Sunnyvale, Calif. (AAS

Preprint 57-40). The fundamental principles of automatic navigation have been well established and navigation systems utilizing these principles have been operated over ranges up to several thousands of miles. However, universal use of automatic navigation systems is for the future. Among navigation systems are (1) a combination of successive position fixing and dead reckoning, (2) a system based on ground speed using a reference heading and maintaining surveillance on track or present position, and (3) systems based on the mechanization of the celestial navigation problem.

Techniques are described for interplanetary travel, such as those based on velocity measurements and celestial sight taking involving the sun and planets. It is pointed out that interplanetary navigation is complicated compared with aerial navigation since it involves six dimensions of the vehicle (three position and three velocity components), six of the destination, and time. A comparison of terrestrial and interplanetary navigation systems is made, and consideration is given to plotting position and velocity for space vehicles and computing fuel consumption for course corrections.

Heat Transfer and Fluid Flow

(28) *On the Generation of Temperatures to 30,000° K*, Peter E. Glaser, Arthur D. Little Co., Cambridge, Mass. (AAS Preprint 57-35). The need for further research at high temperatures is briefly explained and various conventional methods of heating materials in controlled atmospheres are pointed out. The convenience of using electro-magnetic radiation from a suitable source, instead of the source environment itself, and the application of imaging furnaces using solar energy or high-intensity electric arcs are discussed in some detail. The techniques of stabilized gas vortex arcs are described and high-temperature limits mentioned. Future developments for research in even higher temperature ranges are indicated.

Materials, Structures and Vehicle Design

(29) *Beryllium: Promising Metal of the Space Age*, Reginald E. Foster and Louis A. Riedinger, Structures Dept., Missile Systems Division, Lockheed Aircraft Corp., Sunnyvale, Calif. (AAS Preprint-57-3). General weight, strength, and thermal properties of beryllium are discussed. Examples of beryllium application are given which show reduction of weight and thermal stresses in high-temperature environments. Specific weight reductions are demonstrated for a ballistic missile and a lunar rocket.

(30) *Prediction of Cratering Caused by Meteor Impacts*, Maury Kornhauser, Missile and Ordnance Systems Dept., General Electric, Philadelphia, Pa. (AAS Preprint 57-33). Data from high-speed laboratory experiments, explosive craters, and meteorite impacts are correlated to obtain an approximate expression for depth of penetration in terms of target material properties and kinetic energy of the impacting particle.

Propellants and Propulsion

(31) *A Survey of Propulsion and Space Dynamics*, Douglas B. Cross and Jorgen Jensen, The Martin Co., Baltimore, Md. (AAS Preprint 57-1). A combination of space dynamics and available propulsion is the dominating factor in determining the design of space vehicles. The development of propulsive systems for space flight is shown in relation to three steps in the growth of missile and rocket knowledge: (1) boosted flight only (the ballistic missile), (2) boosted flight with relatively small auxiliary propulsive means (a manned satellite), and (3) boosted flight with sustained or intermittent in-flight power (a true space vehicle). Means of propulsion, including chemical nuclear, solar, ionic, and photonic, are discussed.

(32) *Plasma Motors*, Winston H. Bostick, Stevens Institute of Technology, Hoboken, N. J. (AAS Preprint 57-2).

(33) *On Plasma Propulsion*, Yusuf A. Yoler, Missile and Ordnance Systems Dept., General Electric Co., Philadelphia, Pa. (AAS Preprint 57-45). The need for a technique of propulsion intermediate to that of chemical and ionic propulsion is indicated from the point of view of propulsion efficiency. A simple theoretical model on magnetohydrodynamic propulsion on breathing and rocket engines is set up, and results are presented indicating the significant parameters, the nature of magnetohydrodynamic power, and the feasibility of plasma propulsion.

(34) *The Use of Planetary Atmospheres for Propulsion*, Sterge T. Demetriades and Carl B. Kretschmer, Aerojet-General Corp., Azusa, Calif. (AAS Preprint 57-46). The upper atmosphere of a planet serves as a storage tank for the sun's energy. Thus one cm^3 of the Earth's atmosphere at 100 km contains approximately 10^{-6} cal of available energy in the form of atomic oxygen. This offers an inexhaustible supply of energy for propulsion and other purposes.

It is possible that the ultraviolet emission of the sun produces useful quantities of free radicals and dissociated molecules in the atmospheres of the other planets. A provisional table of atmospheric composition of the planets is presented. The composition of the various atmospheric layers and the efficiency of utilization of their energy content depend on the reaction kinetics of the available species. Thus the rational design of an atomic-oxygen power plant for operation in the Earth's atomic-oxygen layer requires knowledge of the recombination rate of atomic oxygen.

This paper presents the reaction kinetics of atomic oxygen in the Earth's upper atmosphere and a preliminary analysis of an atomic-oxygen propulsion unit. Estimates are presented of the mechanism and magnitude of the recombination rates for atomic oxygen in the homogeneous phase as well as of the recombination rates in a heterogeneous system (i.e. on a catalytic surface). These estimates are based on the results of collision rate theory, absolute reaction rate theory, and the interpretation of experimental data available in the literature on other three-body recombination reactions and surface-recombination reactions. Assuming 100% efficiency in utilizing the atomic-oxygen recombination energy, a thrust of 40 dynes per cm^2 of inlet area is obtained. This thrust is independent of the flight speed and depends on the altitude only; it compares favorably with the expected drag at those altitudes at low flight speeds.

Atomic nitrogen is thought to be present in the upper atmosphere of Mars and the thrust-to-drag ratio at orbital velocity could be favorable there. The ideal-thrust-to-minimum-drag ratio is generalized for any recombination power plant in any planetary atmosphere and it is shown that as a first approximation this ratio is independent of altitude and absolute concentrations.

Space Flight Mechanics

(35) *Returning Alive from Space*, Fred R. Riddell and R. W. Detra, Avco Research Laboratory, Everett, Mass. (AAS Preprint 57-4). The major problems in returning a man alive from space are encountered in re-entering the earth's atmosphere at very high velocities. During re-entry the basic physiological problem is to keep the deceleration within tolerable human limits while the principal aerodynamic problem is to prevent the vehicle from being destroyed by the high rate of heat transfer. In addition, there is the problem of effecting the final landing at a suitable location on the earth's surface.

Both lifting and non-lifting or pure-drag manned vehicles

(*Continued on page 30*)

NEWS OF THE AAS

FIG. 1. Professor Winston H. Bostick presenting a paper on Plasma Motors.

FIG. 2. Registrants at the IV Annual Meeting: (from left to right) Dr. George Arthur (VP), Norman V. Petersen (AAS Director), Colonel Paul A. Campbell (Technical Session Chairman), Saunders Kramer (AAS member), and Ross Fleisig (AAS President).

FIG. 3. Registrants at AAS IV Annual Meeting

V Annual AAS Meeting

The American Astronautical Society held its Fourth An-ual meeting on January 29–31, 1958 at the Engineering Soci-ties Building in New York City. The technical papers related o six areas of space technology, *Space Vehicle Design, Guid-nce and Control Techniques, Man's Environment in Space, Space Vehicle Communications, Astronautics Research,* and *Space Exploration.*

To expedite publication of these papers prior to their ap-earance in the *Journal*, 36 technical papers have been released n bound form in the *Proceedings of the IV AAS Annual Meet-ng* to appear in early July. Single copies of many of the con-ributions are still available in Preprint form on order from he Society.

Technical Sessions Chairmen

The Technical Session Chairmen included: *Jorgen Jensen*, The Martin Co.; *Dr. William E. Frye*, Lockheed MSD.; *Col. Paul A. Campbell, USAF*, Office of Scientific Research; *Louis A. G. terVeen*, Lockheed MSD.; *Robert P. Haviland*, General Electric Co.; *Kelsey Walker*, Ramo-Wooldridge Corp.

IV Annual AAS Awards

The AAS Space Flight Award for 1957 was given to *Dr. Wernher von Braun*, Army Ballistic Missile Agency, Redstone

IX Annual Congress

of the

INTERNATIONAL ASTRONAUTICAL FEDERATION

DATE—

August 25 to 30, 1958

PLACE—

Amsterdam, Netherlands

REGISTRATION—

Type or write in block capitals the following information: Family name, First name, Profession, Address (street and no.), City and county, names of others in party, and affiliation or company name. Send this registration information to:

Mrs. A. F. P. Volten
℅ Secretariat, IAF Congress
27, Molenstraat, The Hague, Netherlands

Registration fee (including the excursion): f 60
The entrance fee of f 25.- must be paid in advance to the Amsterdamse Bank, 14 Wagenstraat, The Hague, in favour of NUFFIC (IAG Congress). The entrance fee is not refundable. The balance (f 35.-) can be paid on arrival.
Closing date for registration: March 31st.

HOTEL ACCOMMODATIONS—

Request hotel accommodations from:

Tourist Office
Lissone Lindeman N.V.
5 Leidse Straat
Amsterdam, Netherlands

TECHNICAL PAPERS—

It is recommended that AAS members and Journal subscribers forward their Technical Papers (Enclose 3 copies) to Dr. Horace Jacobs, Chairman of the AAS Technical Papers Committee, at the society secretarial address. Dr. Jacobs will submit the papers to the IAF Papers Selection Committee.

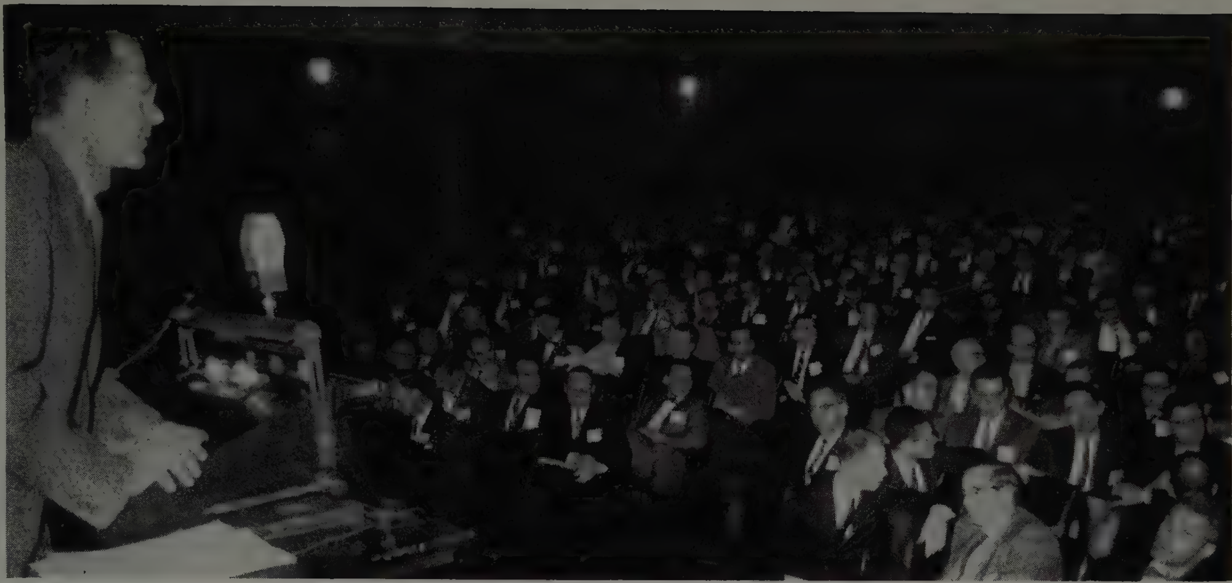

FIG. 4. Jorgen Jensen, Technical Session Chairman on Space Vehicle Design, being questioned from the audience at the opening meeting.

Arsenal, Alabama. The accompanying scroll (Fig. 10) was accepted for Dr. von Braun by *Austin N. Stanton*, AAS Director, and President, Varo Manufacturing Company.

The Melbourne W. Boynton Award in Space Medicine awarded for the first time in 1958 was presented to *Major David G. Simons, USAF*, Air Force Missile Development Center, Holloman Air Force Base, Alabama, by the Commandant of the USAF School of Aviation Medicine, *Major General Otis O. Benson Jr.* (Fig. 11).

Fellow Awards acknowledging special efforts and achievements in the field of astronautics were presented during the Honors Night Dinner to the following: *Colonel Paul A. Campbell*, Office of Air Force Research; *Dr. Allan B. Crunden Jr.*, Montclair, N. J.; *Rear Admiral Luis DeFlorez, USN (Ret.)*; Krafft A. Ehricke, *Convair Astronautics Div.*; *Robert P. Haviland*, General Electric Co.; *E. H. Heinemann*, Douglas Aircraft Co.; *Commander George W. Hoover Jr.*, Office of Naval Research; *Jorgen Jensen*, The Martin Co.; *Dr. I. M. Levitt*, The Franklin Institute; *Norman V. Petersen*, Lockheed MSD; *Major David G. Simons, USAF*; *Dr. Wernher von Braun*; and *Fred S. Whipple*, Harvard Observatory.

FIG. 5. Informal discussion between sessions at the IV Annual Meeting: (left to right) Professor Fred L. Whipple, Richard Wehrlin (1957 AAS Director), and Comdr. George W. Hoover Jr.

Astronautica Acta

By special arrangement with the publisher, the society is pleased to offer to its membership yearly subscriptions to ASTRONAUTICA ACTA at a reduced price. ASTRONAUTICA ACTA is published quarterly as the official journal of the International Astronautical Federation. AAS members who wish to subscribe to ACTA are requested to send their name and address to which the journal will be mailed together with a check (made out to the American Astronautical Society) and the volumes desired to the Corresponding Secretary at the society address. The subscription rate is $7.80 per year including postage. The volumes which may be ordered at this time are Volume IV (1958) as well as Vol. I, II and III for 1955, 1956, 1957, respectively.

FIG. 6. A group of AAS officers and directors attending the Annual Business Meeting of the Society: (left to right) N. V. Petersen, Jorden Jensen (VP), George Nestor (Treas.), George Arthur (VP), Ross Fleisig (Pres.), Al Mayernik (Secy.), and Leroy McMorris (Secy.).

Fig. 7. Welcome W. Bender, Vice President and Director, RIAS, Baltimore, Maryland addresses the Society at the Honors Night Dinner. Mrs. Ross Fleisig and Mrs. Norman V. Petersen are to his right.

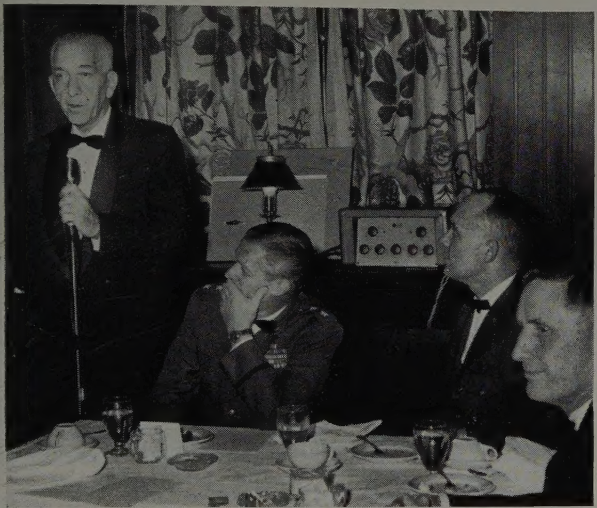

Fig. 8. H. E. Weihmiller, 1957 Chairman, AAS New York Section, welcomes guests at the IV Annual Honors Night Dinner at the Midston House. To his left are Major General Otis O. Benson Jr., Major David G. Simons, and Austin N. Stanton (AAS Director).

Fig. 9. Dr. Dael Wolfle, Executive Officer, American Association for Advancement of Science, discusses AAS affiliation with AAS President Ross Fleisig.

1957 Space Flight Award

PRESENTED TO

Wernher von Braun

JANUARY 29, 1958

Pioneer in Modern Astronautics

His driving spirit, organizing genius, imagination and foresight produced the first operational missile, a significant step toward space flight.

Pioneer in space vehicle design, his concepts led the way toward practical ships of the future.

Leader in organizations dedicated to astronautics, his influence inspired many in the field.

The first feasible minimum satellite and launching system based on proven missile components was proposed by him.

American Astronautical Society
IV ANNUAL MEETING · NEW YORK CITY

Fig. 10. Reproduction of scroll accompanying the 1957 AAS Space Flight Award presented to Dr. Wernher von Braun. The Award was accepted for Dr. von Braun by Austin N. Stanton, President Varo Manufacturing Company.

Fig. 11. Maj. Gen. Otis O. Benson, Jr., USAF (MC) Presenting Melbourne W. Boynton Award to Maj. David G. Simons, USAF.

Abstracts and Reviews of the Astronautical Sciences

(*Continued from page 24*)

have been proposed for accomplishing safe return from space to the earth's surface. The relative merits of these two classes of vehicles are considered. It is concluded that the pure-drag reentry vehicle has inherent advantages over the lifting vehicle which advantages will continue to exist until major technological advances are made, particularly in the field of rocket propulsion.

(36) *Optimum Thrust Programming along Arbitrarily Inclined Rectilinear Paths*, Angelo Miele, School of Aeronautical Engineering, Purdue University, Lafayette, Ind. (AAS Preprint 57-6). An analysis of the theory of thrust programming is presented for the case where a variable mass body is moving along an arbitrarily prescribed rectilinear path. The variational problem is treated within the general frame of problems of the Mayer type, i.e., as the problem of minimizing the difference ΔG between the values which a function G of the generalized coordinates of the missile assumes at the end-points of the trajectories. By the use of indirect methods of the calculus of variations it is shown that the totality of extremal arcs is composed of zero-thrust sub-arcs. General results are obtained—some of them in a closed form—including, as a particular case, previous work developed by Hamel, Tsien, Evans, Hibbs, Cicala, Miele, Leitmann and Ward. Several numerical examples are included, emphasizing the engineering aspects of the present theory in connection with astronautical applications.

(37) *Minimum Time Interplanetary Orbits*, Dandridge M. Cole, Advanced Systems Requirements, The Martin Company, Denver, Colo. (AAS Preprint 57-39). A brief review is presented of the work of Lawden and others on minimum-energy interplanetary orbits. The argument is presented that interest will be transferred from minimum-energy to minimum-time orbits when efficient nuclear propulsion systems become available. Results of calculations on continuous-thrust travel times to the moon and the planets are discussed for manned and unmanned vehicles. It is concluded that space flight may take on aspects of economic utility and extra-terrestrial colonies may become feasible when these new power-sources become available.

A Survey of Propulsion and Space Dynamics

(*Continued from page 19*)

would take 49 hr. If minimum energy techniques were employed the trip would take 100 hr.

It is obvious that propulsion is the key to the problem of space flight and that actual manned interplanetary flight will be accomplished with sustained or intermittent in-flight power. Under these conditions, we can achieve short flight times, absolute control over flight profiles and force environment, and economic compatibility with mission results, thereby adding the space vehicle to our expanding means of transportation and communication.

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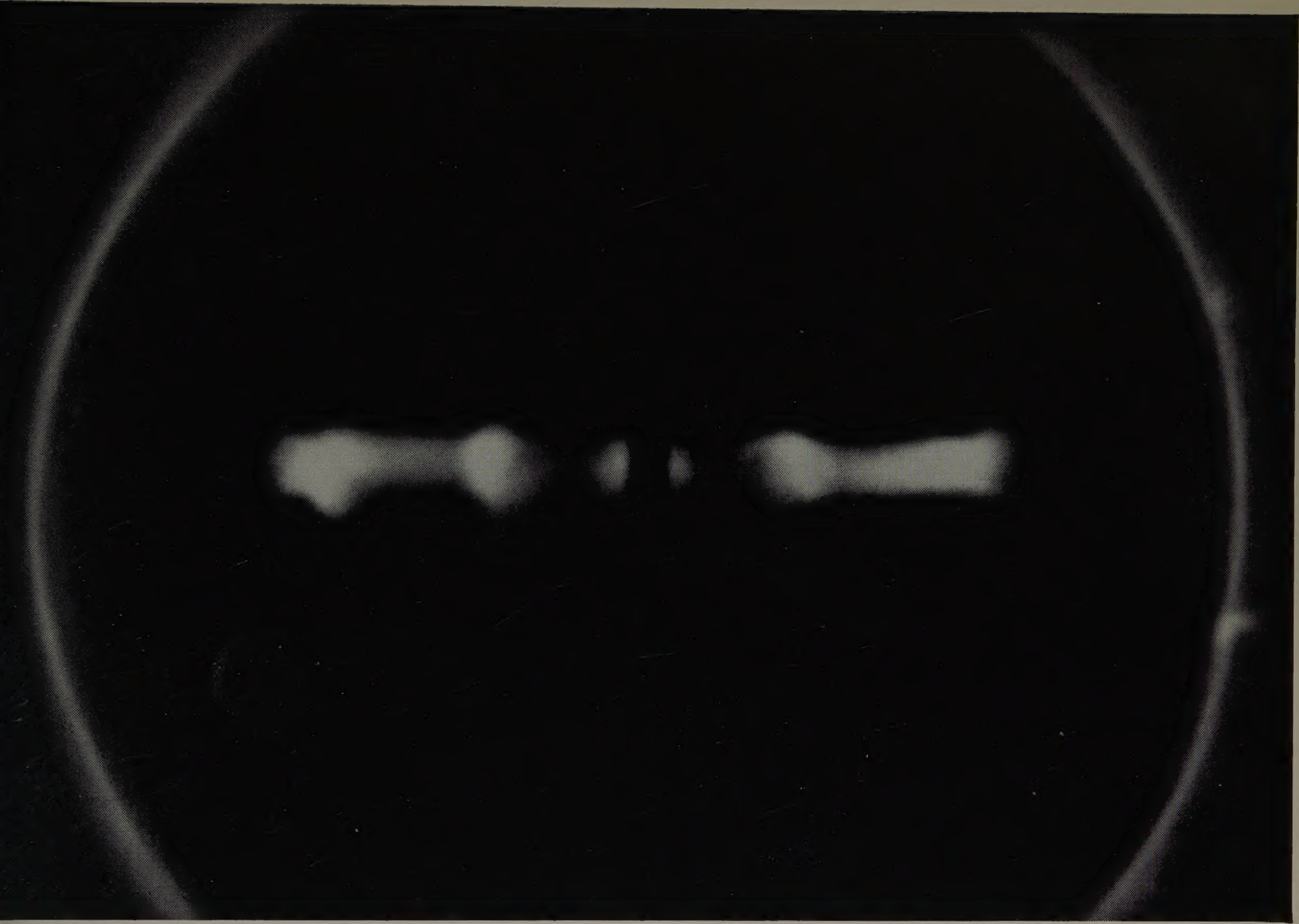
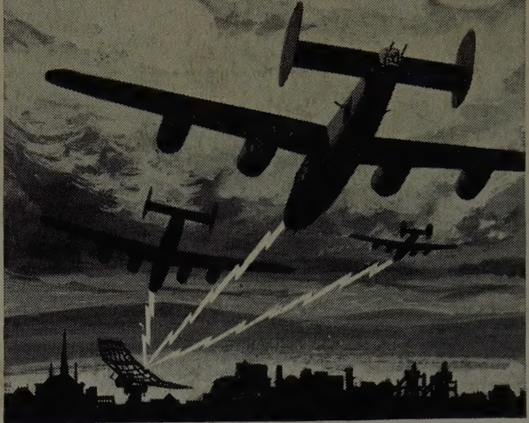


1942 First effective radar countermeasure was "Window," code name for thin strips of metal foil which reflected spurious radar echoes when dropped from Allied bombers, confusing enemy radar operator.



1943 Next came "Carpet," designation for techniques of radiating "noise" or static from bomber-borne transmitters, each tuned to slightly different frequency. Torrent of "noise" produced "rippling grass" pattern on enemy radarscope.

1944 "Tuba" was a tremendously powerful (50,000 watts) jamming transmitter located in England. Its potent signal blinded German night fighters' radar as they pursued RAF formations toward the island.

THE STORY BEHIND THE STORY

COUNTER-MEASURES

U. S. MAKES PROGRESS IN DECEIVING AN ENEMY

TODAY Shown below is only one of the techniques used in Sperry's integrated countermeasures system. U. S. bomber sweeping inland toward target nears anti-aircraft missile installation. Normally, bomber appears as blip on ground radarscope (1). But new Sperry jammer would transmit countersignal on same frequency as enemy radar, completely obscuring echo of signal on ground radarscope (2). This would make it impossible for enemy to tell number, location, or direction of U. S. planes.

Protecting our strategic bombers from detection is a unique military problem. For example, if enemy radar detects our bombers they cannot accomplish their mission. The problem then is to make the enemy's radar ineffective. Jamming techniques employed in World War II were effective in varying degrees but are inadequate today.

Now Sperry can report a notable break-through in this little-publicized area of electronics, achieved in cooperation with USAF's Air Research and Development Command. An integrated countermeasures system will equip SAC's Boeing B-52s with "a bag of tricks" which not only jams radars but also deceives missiles. This versatile system promises to provide a new measure of protection for our superbombers and will considerably enhance their offensive effectiveness.

ELECTRONIC COUNTERMEASURES DIVISION

SPERRY *GYROSCOPE COMPANY*
Great Neck, New York

DIVISION OF SPERRY RAND CORPORATION